

EDITOR
DR. MELİKE BÜŞRA BAYRAMOĞLU KARŞI

PRESERVING THE PAST: SUSTAINABLE SCIENCE IN CULTURAL HERITAGE



BZT TURAN

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DR. MELİKE BÜŞRA BAYRAMOĞLU KARŞI



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Dr. Melike Büşra BAYRAMOĞLU KARŞI

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Preface

It is with great pleasure that we present this volume, which brings together five interdisciplinary studies at the intersection of cultural heritage conservation, urban studies, and sustainable architectural practices. The preservation of historical structures and artifacts is not only a matter of maintaining physical integrity but also a means of safeguarding the cultural, social, and environmental narratives that these spaces embody. This volume emphasizes both the technical and socio-cultural dimensions of heritage preservation, providing insights into contemporary methodologies and their practical applications.

The first chapter, “From Çatalhöyük to the Present: Water-dependent Housing Settlement Patterns and Sustainability in Konya”, explores the long-standing relationship between water resources, agricultural practices, and housing design. By examining historical and contemporary settlements, the chapter demonstrates how traditional construction and settlement patterns contribute to sustainable water management and offer lessons for modern ecological challenges.

In the second chapter, “Evaluation of Street Rehabilitation Applications in the Historic Midyat Syriac Bazaar in Terms of Sustainable Conservation”, the focus shifts to the revitalization of historic urban spaces. Using comprehensive fieldwork and spatial analysis, this study highlights the importance of integrating social, cultural, and economic dimensions alongside physical conservation measures to maintain the living identity of historical bazaars.

The third chapter, “Industrial Heritage and Spatial Justice Inequality through Creative Labor: A Comparative Reading of Santral İstanbul and Tate Modern”, addresses the transformation of industrial heritage sites under creative economy frameworks. Through a comparative lens, it critically examines how institutional and governance differences influence public accessibility, authenticity, and spatial justice in repurposed industrial environments.

The fourth chapter, “Capillary Moisture in Historical Masonry Structures: Damage, Diagnosis and Technology”, presents a thorough investigation

of rising damp in historic masonry buildings. This work underscores the importance of accurate diagnosis and appropriate technological interventions to mitigate moisture-induced deterioration while preserving structural and material integrity.

Finally, the fifth chapter, “Nd:YAG Laser Cleaning in the Conservation of Stone Cultural Heritage: International Case Studies”, explores innovative laser cleaning techniques for the preservation of stone artifacts. Highlighting the selective and controlled removal of dirt and biofilms, the study demonstrates the potential of Nd:YAG laser applications to achieve effective conservation outcomes with minimal physical impact.

Collectively, these chapters illustrate the diversity and complexity of contemporary heritage conservation. They reflect an integrative approach that combines scientific analysis, technological innovation, and socio-cultural awareness, offering valuable guidance for practitioners, researchers, and policymakers. It is our hope that this volume will serve as a resource for advancing sustainable and holistic strategies in the preservation of both tangible and intangible heritage.

We extend our sincere gratitude to all contributing authors for their rigorous scholarship, as well as to the reviewers and editorial team whose efforts have ensured the high academic quality of this publication.

Dr. Melike Büşra Bayramoğlu Karşı

Editor

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Aybike Sila Aykaç Selamoğlu

CHAPTER 1

From Çatalhöyük To The Present: Water-dependent Housing Settlement Patterns And Sustainability In Konya

Rabia Çil¹

Abstract

The Konya Basin has historically hosted diverse settlement patterns shaped by the availability of water resources. This study comparatively examines three settlements from different historical and socio-cultural contexts—Çatalhöyük, Sonsuz Şükran Village, and Ormana Buttoned Houses—through the lens of the relationship between water, agriculture, and housing. The research evaluates how water scarcity has influenced housing design and spatial organization over time and analyzes the potential of traditional construction practices in contributing to sustainable water management. The findings reveal that indigenous knowledge and traditional lifestyles may offer valuable alternative approaches to contemporary ecological crises.

Keywords: Water management, sustainability, Konya, Çatalhöyük, traditional housing, ecological design, rural architecture

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INTRODUCTION

Throughout human history, water resources have played a decisive role in shaping settlements. Especially in the interior regions of Anatolia, located within the arid climate belt, access to water has directly influenced the positioning and spatial organization of living areas. The Konya Basin stands out as an important settlement area in this context from prehistoric periods to the present. The region possesses a rich accumulation in terms of dependency on natural water resources, drought, and water management strategies throughout history (Karpuz, n.d.).

This study examines how settlements in the Konya Basin have been shaped based on water, within the context of historical continuity and spatial transformation. Through the examples of Çatalhöyük from the Neolithic period, Ormana Buttoned Houses from traditional Ottoman architecture, and Sonsuz Şükran Village with its modern ecological approaches, the relationships between water, agriculture, and housing in traditional and contemporary settlements will be addressed from a sustainability perspective. The study seeks answers to the following research questions:

- Why did housing settlements develop in areas close to water, and what kinds of spatial adaptations did they demonstrate in the face of water scarcity?
- What potential do traditional building systems and life practices carry today in terms of sustainable water management?
- What lessons does the water–housing relationship in different historical and cultural contexts offer to contemporary architectural and urban practices?

METHOD

This study employs a comparative case analysis based on a qualitative research method. Within the scope of the research, three settlements belonging to different historical periods and socio-cultural contexts, which are significant in terms of the water–housing relationship in the Konya Basin, were selected: Çatalhöyük from the Neolithic Age, Ormana Buttoned Houses from the Ottoman Period, and Sonsuz Şükran Village from the modern period. These examples were analyzed in detail based on predetermined criteria such as settlement history, form of access to water, building materials, spatial organization, and sustainability strategies.

During the data collection process, relevant academic publications (scientific articles, master's theses), archaeological reports, official documents (State Hydraulic Works reports, municipal strategy documents), and observations based on field research were utilized. The collected data were comparatively examined in line with the determined criteria, and each settlement's water adaptation strategies and sustainability potential were qualitatively evaluated. This method aims to deeply understand the water-housing interaction across different historical processes and to draw inferences from traditional knowledge accumulation for contemporary sustainability approaches.

THEORETICAL FRAMEWORK

Water is not only a natural resource but also a cultural element that shapes many decisions, from the positioning of settlements to building technologies, and from social relations to cultural practices (Aslantürk, 2022). Especially for arid and semi-arid basins, water scarcity has turned into a critical sustainability issue along with climate change and increasing urbanization (Demir, 2025; DSİ, 2024). Therefore, the relationship that historical structures have established with water contains important lessons for contemporary architecture and planning.

With climate change, the decrease in water resources, and the increase in urbanization, water-sensitive planning and ecological design strategies have gained even greater importance today. In semi-arid climate regions such as Türkiye, the balance observed in the use of natural resources within the spatial patterns of traditional settlements provides significant data that can inspire contemporary planning approaches (Aslantürk, 2022). In this context, blending the wisdom of past water management practices with modern solutions is considered a critical approach for the sustainable settlements of the future.

The Falkenmark Index, developed by Falkenmark, Lundqvist, and Widstrand (1989), is based on the relationship between a country's total population and its renewable freshwater resources. This index takes into account not only the water requirements of domestic, agricultural, industrial, and energy sectors but also the water needs of natural ecosystems. As stated, an annual renewable water amount of 1700 m³ per capita is accepted as a threshold at which water stress is not experienced. When this threshold value is fallen below, the region enters water stress; less than 1000 m³ per capita is classified as water scarcity, and less than 500 m³ per capita as absolute water scarcity. This classification is summarized in Table 1. The main reason for the widespread acceptance of the method is the ease of access to data and its simplicity of use. However, the index also has some limitations. First, annual average values given at the national scale may conceal water scarcity at the local scale. In addition, it does

not take into account infrastructure facilities that affect water availability and overlooks variables such as lifestyle or climate conditions in different countries.

Table 1. *Water Stress Classification According to Falkenmark Index Values*

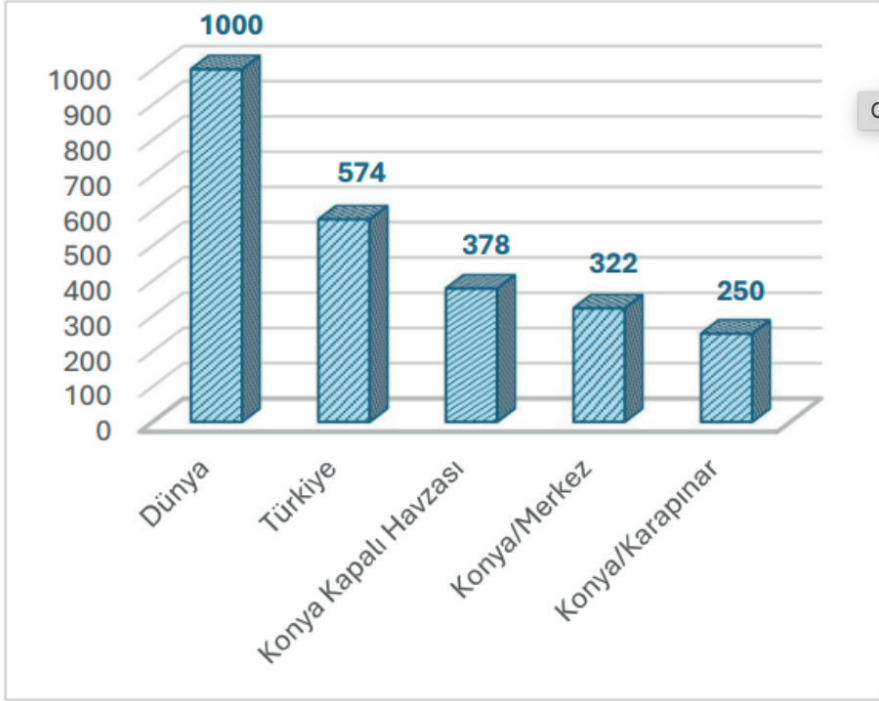
Per Capita Water Amount (m ³ /year)	Classification
≥ 1700	Area without water problems (no stress)
1700 – 1000	Area experiencing water stress
1000 – 500	Area experiencing water scarcity
≤ 500	Area experiencing absolute water scarcity

In line with the values encountered in the Falkenmark Index, a water assessment for the province of Konya was conducted in accordance with this index in a document published on the KOSKİ homepage by KOSKİ General Manager Ahmet DEMİR. The data in this assessment are presented as follows:

“Countries are classified worldwide according to the amount of water per capita as follows:

- *Above 10,000 m³/year: Water-rich country*
- *7,000–10,000 m³/year: Country with comfortable water resources*
- *4,000–7,000 m³/year: Country with sufficient water resources*
- *1,000–4,000 m³/year: Country experiencing water stress*
- *Below 1,000 m³/year: Water-poor country*

In Türkiye, the per capita water amount is approximately 1,320 m³/year, and if the current population growth continues, there is a risk that after 2030 this figure will fall below 1,000 m³/year, placing our country in the position of a ‘water-poor’ country.



Dünya, Türkiye ve Konya'da Yağış Dağılı

Konya Closed Basin Water Potential

- Usable Surface Water: Approximately 1,930,000,000 m³ annually
- Usable Groundwater: Approximately 2,435,000,000 m³ annually

In total, there are approximately 4.365 billion m³ of water in the Konya Closed Basin.

2.3. Actual Water Use

The amounts of water actually used are as follows:

- Surface Water Use: 2–2.5 billion m³ annually
- Groundwater Use: 4–4.5 billion m³ annually

On average, 6.5 billion m³ of water is used annually in the basin.

This situation shows that, in addition to the existing reserves, approximately 2.375 billion m³ of extra water is withdrawn through approximately 115,000 uncontrolled illegal wells. The water withdrawn from illegal wells causes at least a 3-meter annual decline in groundwater reserves; if this trend continues, an additional 90-meter decrease in groundwater levels is expected by 2050. Today, in some regions, the water level has dropped to as deep as 200 meters.”

It is possible to perceive from the information presented above how water affects not only consumption but also agriculture and life itself. Water, along with related phenomena, at some point brings to mind the concept of sustainability. The effects of policies implemented in a sustainable manner are important for the conservation of water resources and, consequently, for the considerations necessary in terms of settlements.

Sustainability, in its simplest definition, refers to the use of resources in a way that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987). This concept is examined in three main dimensions: environmental, economic, and social. In this respect, sustainability is a holistic approach that not only involves environmental protection but also ensures the continuity of economic development and the achievement of social equity.

The principle of sustainability gained a central place in international policy documents, urban planning, and disciplines related to the built environment, such as architecture, especially during the last quarter of the 20th century as environmental crises increased. Issues such as climate change, biodiversity loss, rapid urbanization, and depletion of natural resources have transformed sustainable development from a choice into a mandatory approach (Kates et al., 2005).

The reflections of sustainability in different disciplines also reveal the multidimensional nature of the concept. For example, in environmental sciences, sustainability is generally associated with the continuity of ecosystems, whereas in architecture and urban planning, it is concretized through criteria such as energy efficiency, carbon footprint reduction, and water cycle management (Yücesoy & Yılmaz, 2018). In this context, sustainability is not limited to the goal of protecting nature; it also encompasses the long-term resilience of settlements, the built environment, and social structures.

In research conducted to emphasize the importance of the water cycle and residential settlements near water in the context of sustainability, one of the concepts encountered was the notion of “Habitus.”

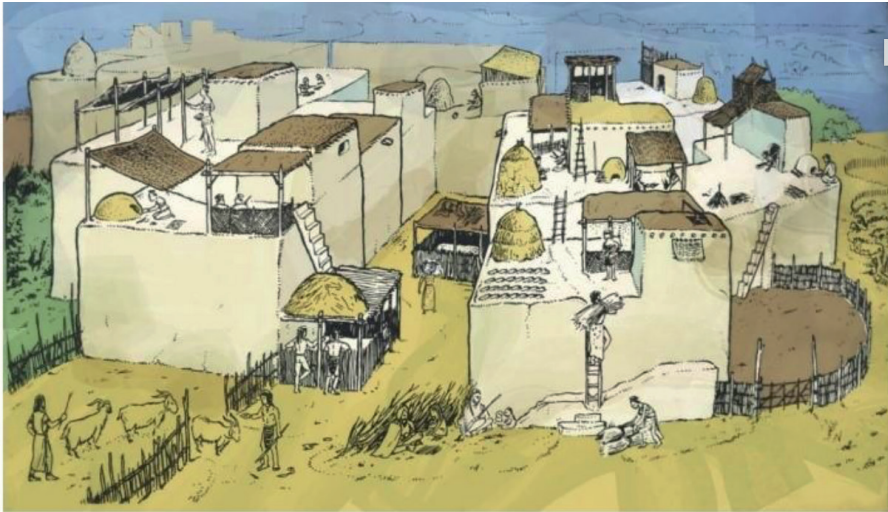
Habitus refers to the systems of thought, perception, and action that individuals and communities acquire within a set of cultural practices and values (Aslantürk, 2022). In rural settlements, water management has often been rooted in this habitus, shaped by local knowledge and traditional practices passed down through generations. These practices constitute the habits and values that the community has developed regarding access to, use of, and management of water. The spatial culture developed in relation to water

determines the community's collective sense of belonging, architectural fabric, and cultural identity regarding water access and use. This cultural context demonstrates that water has become more than just a physical necessity; it is a fundamental component of social life and spatial organization. Rural aesthetics, in turn, reflect building techniques harmonious with the natural environment, the use of local materials, and collective production methods. In this context, traditional houses, construction techniques compatible with nature, and the use of local materials possess qualities that could serve as a model for sustainable architecture today.

THE WATER-BASED SETTLEMENT HISTORY OF THE KONYA BASIN AND SAMPLE ANALYSES

The Konya Basin has had a rich tradition of water-based settlement since prehistoric times. The relationship that settlements in the region established with water was not limited to meeting vital needs; it also played a decisive role in shaping social relations, agricultural production, and architectural spaces. From the Hittite period to the Ottoman era, wells, cisterns, fountains, and water channels built in the region demonstrate that water has always been an integral part of the settlement fabric (Karpuz, n.d.).

Çatalhöyük: The Relationship with Water and Land in the Neolithic Period



Çatıların önemini gösteren Çatalhöyük canlandırımı. (İllüstrasyon: John Swogger)

FIGUR 1, URL-1

Çatalhöyük, dated to 7400–6200 BCE as a Neolithic settlement, features early residential arrangements that integrate the relationship between agriculture and water (Çiçek & Erdoğan, 2024). Located near the Çarşamba River in a wet and alluvial area, the settlement developed unique spatial adaptations to mitigate flood risks.

Structures were built in a contiguous layout, with no streets between them, and access to houses was through the roof (Çatalhöyük Research Project, n.d.a). This dense construction is interpreted as a measure developed both for defense and protection against potential flood events. Roof access also helped preserve the compact structure of the settlement, allowing for more efficient use of agricultural land. The windowless and solid walls of the houses are also thought to be adaptations against water inundation (Ekşi Şeyler, n.d.). Inside, homes contained hearths, raised platforms, and storage areas. Locally available materials such as mudbrick, reed, and wood were used for construction (Çatalhöyük Research Project, n.d.b).

The main water sources for Çatalhöyük were the Çarşamba River and groundwater. Archaeological evidence suggests the use of simple irrigation channels and wells (Republic of Türkiye Ministry of Agriculture and Forestry, n.d.). There is also evidence that wastewater was collected under some latrines using clay pipes, indicating a rudimentary wastewater management system for the period (Republic of Türkiye Ministry of Agriculture and Forestry, n.d.). However, there is no clear evidence of complex systems specifically designed for rainwater harvesting or the direct use of courtyards for water collection. Water management was primarily focused on adapting to natural resources and reducing risk.

Sonsuz Şükran Village: Traditional Forms and Contemporary Approaches



FIGURE 2, URL-2

Located in the Hüyük district of Konya, Sonsuz Şükran Village, established by artists after 2011, is a modern settlement built based on traditional Anatolian house architecture. Local materials such as stone, mudbrick, and wood are used in the settlement, yet it holds the potential to go beyond traditional methods

in water management. The village provides an experimental field for how modern sustainability approaches can be integrated with traditional structures (Köktürk & Gökçen Dündar, 2018).

Studies indicate that while widespread rainwater harvesting or greywater treatment systems are not yet present in the village, adopting such practices within an ecological framework could enhance its sustainability potential (Çoban et al., 2024). This suggests that water management is still largely limited to individual solutions, and collective systems based on local water knowledge have not yet been sufficiently developed. Nevertheless, the presence of individual water-saving awareness in daily life and gardens supporting agricultural production demonstrates a sensitivity toward efficient water use. As a community-based settlement, the village carries significant potential for developing collective water management and sustainability awareness. Approaches such as implementing greywater systems and avoiding impermeable surfaces are steps taken to support sustainability.

Ormana Düğmeli Houses: Adaptive Architecture in a Water-Scarce Landscape



FIGURE 3, URL-3

The “buttoned” houses in Ormana Village, located in the İbradı district of Antalya, are traditional rural dwellings constructed using stone and wood with a unique, mortar-free building technique. The “buttoned” construction method connects stone walls with wooden beams, providing flexibility to the structure. Situated on sloped terrain with limited surface water, these houses

have enabled sustainable living for centuries in a water-scarce environment (Aslantürk, 2022).

The scarcity of water resources in the region directly influenced the structural design of the houses and their water management strategies. Household water needs were met through water transported from wells, cisterns, and fountains (Kalemişi Magazine, n.d.). In particular, cistern systems for collecting rainwater were critically important for the sustainable use of water (Özdeş, 2017). The creation of storage areas in the lower sections of the houses and the use of spaces called “hamamlık” or “çağlık,” where wastewater was directed outside through sloped floors and pipes, demonstrates traditional indoor water-use efficiency (Kalemişi Magazine, n.d.). These systems allowed water to be used carefully and cyclically within the home. The building design, sensitive to topography and climate, clearly shows that water was not merely a need but a fundamental determinant of spatial organization. These houses are a tangible example of how local knowledge and adaptation to environmental conditions are reflected in architecture.

Comparative Evaluation Table

Table 1 summarizes the main characteristics of the examined settlements in the context of water, agriculture, and housing relationships. These criteria were determined based on widely used indicators in the literature to understand the relationship of traditional houses with water, the use of materials, and spatial adaptations.

Table 2. Water-Related Characteristics of Konya Basin Settlements: A Comparative Evaluation

Criteria	Çatalhöyük	Sonsuz Şükran Village	Ormana Buttoned Houses
Settlement Period	Neolithic Age (B.C. 7400–6200)	Modern Period (After 2011)	Ottoman Period (17th–19th centuries)
Main Water Source	Çarşamba River, Groundwaters	Municipal Network, Potential Rain	Wells, Cisterns, Fountains
Building Material	Adobe, Reed, Wood	Adobe, Stone, Wood	Stone, Wood (Buttoned Technique)
Spatial Organization	Adjacent Layout, Entrance from Roof	Detached Layout, Courtyard System	Compact Courtyard Structure
Water Management Strategy	River/Well Access, Simple Irrigation Channels, Flood Adaptation	Individual Water Saving Awareness, Gardens, Potential Grey Water/Rainwater Harvesting	Collecting Rainwater in Cisterns, Wells, Indoor Drainage

Sustainability Approach	Based on Natural Necessity, Collective Adaptation	Conscious and Ecological Choice, Modern Approach	Traditional Experience Based on Adaptation to Scarce Resources
Usage Status	Archaeological Site	Living Settlement (Partially)	Still in Use

**WATER–AGRICULTURE–HOUSING RELATIONSHIP:
EVALUATION FROM A SUSTAINABILITY
PERSPECTIVE**

In all three examined settlements, water occupies a central role in life and directly influences spatial organization. At Çatalhöyük, water ensured the continuity of community life while triggering architectural adaptations against potential floods. The abundance of water shaped the settlement’s dense and inward-facing structure, leading communities to organize shared living spaces according to water sources. In Ormana, water scarcity shaped building practices and fostered an entrenched “water-conscious habitus,” cultivating a culture that emphasizes the value of every drop. Sonsuz Şükran Village, on the other hand, seeks to combine this historical knowledge with contemporary sensibilities and ecological approaches to create a sustainable model.

A common thread among these settlements is that water is not merely a necessity but also a determinant of social organization and spatial formation. Access to and management of water resources brought communities together, shaped collective work practices, and influenced spatial hierarchies. Traditional rural settlements, through collective production methods, nature-compatible construction techniques, and the use of local materials, possess qualities that can serve as models for sustainable architecture today. Passive systems developed to cope with water scarcity (cisterns, permeable surfaces, dense construction) and social practices (careful water use, sharing) offer valuable lessons that can inspire contemporary planning and design approaches. These examples provide tangible evidence of human creativity and adaptive capacity in the face of ecological challenges.

CONCLUSION AND RECOMMENDATIONS

Historical settlement examples in the Konya Basin clearly demonstrate the decisive role of water in spatial organization and the creative adaptations developed in response to water scarcity. Challenges in accessing water have

prompted not only technical solutions but also social and cultural strategies. In this context, the following conclusions and recommendations emerge in light of contemporary ecological crises:

Value of Traditional Knowledge: The efficient use of water in traditional structures, passive climate control with local materials, and settlement layouts adapted to natural resources can serve as models for contemporary ecological architecture. Especially for arid basins, revisiting traditional practices—such as avoiding impermeable surfaces, harvesting rainwater (e.g., through green roofs and vertical gardens in urban areas), and implementing shading systems—and adapting them to modern contexts is crucial for sustainable design.

Integrated and Hybrid Approaches: Enhancing the resilience of modern settlements to water crises can be achieved by combining traditional methods with innovative materials and modern technologies, such as integrating greywater treatment systems into houses and implementing smart irrigation systems. In addition to centralized water infrastructures, household- and community-level water collection and reuse systems should be encouraged. This will increase water security while ensuring the efficient use of local resources.

Water Awareness and Social Participation: As observed in the Konya Basin, water is not merely a consumable resource but also a factor shaping spatial organization. In water-scarce regions, social “water consciousness” and collective management practices are as important as technological solutions. The water-based spatial organization of rural settlements constitutes a heritage worth studying and applying in sustainable design. Strengthening community water-related habitus through education, awareness campaigns, and participatory planning processes will play a key role in the sustainable management of water resources.

This study provides an initial insight into the historical evolution of the water–housing–agriculture relationship in the Konya Basin. Future research could focus on a detailed analysis of traditional water engineering techniques used in these settlements, a deeper examination of local knowledge regarding water, or the potential impacts of climate change on these settlements. In conclusion, these settlements in the Konya Basin reveal the profound relationship between humans and water, highlighting the architectural and cultural dimensions of adaptation to environmental conditions.

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CHAPTER 2

Evaluation of Street Rehabilitation Applications in the Historic Midyat Syriac Bazaar in Terms of Sustainable Conservation

Sevda Aksöz¹

Özge Bozgeyik²

ABSTRACT

The preservation of historic urban fabrics has evolved beyond being a process focused solely on improving the physical environment; it now requires a holistic approach that addresses social, cultural, and economic components together. In this context, historic bazaars stand out as urban spaces that play an important role in the formation of urban identity, the continuity of social memory, and the intergenerational transmission of cultural heritage. This study aims to evaluate the spatial, social, and cultural impacts of street revitalization practices in a multidimensional manner by examining the Historic Midyat Syriac Bazaar in the Midyat district of Mardin within the framework of a sustainable conservation approach.

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The research was conducted using a comprehensive approach. In the first phase, national and international literature on sustainable conservation, street revitalization, and historical market concepts was reviewed. In the second phase, the historical development and spatial and architectural characteristics of the market were analyzed using archival documents, plans, and visual materials. Field studies included site observations, photographic documentation, semi-structured interviews, and surveys of local merchants and visitors. In addition, map-based spatial analyses were used to evaluate functional distribution, facade arrangements, pedestrian mobility, and usage intensity.

In conclusion, it is evident that the street rehabilitation projects carried out in the Historic Midyat Syriac Bazaar did not sufficiently take into account the multi-layered cultural structure of the area and the forms of interaction with the social structure. It is evident that limiting conservation practices in the Historic Midyat Syriac Bazaar to physical interventions alone weakens the living cultural identity of the bazaar and that sustainable conservation is only possible through holistic approaches that center Syriac local merchants and users.

Keywords: Sustainable Conservation, Street Rehabilitation, Historic Midyat Syriac Bazaar

INTRODUCTION

The preservation of historic urban fabrics cannot be limited to structural improvements alone; it necessitates a comprehensive conservation approach that encompasses spatial continuity as well as social and economic sustainability. In particular, globalization, tourism pressure, and rapid urbanization processes accelerate the functional and spatial transformation of unique spaces located in historic city centers; this situation necessitates a reassessment of conservation approaches. In this context, historic bazaars are not merely areas where commercial activities are carried out; they stand out as living urban spaces that play an important role in the formation of urban identity, the continuity of social memory, and the intergenerational transmission of cultural heritage.

Historic markets are unique spaces that directly reveal the socio-cultural character of urban life through the production systems they host, their accumulation of craftsmanship, their network of social relationships, and their spatial configurations. These spaces are dynamic environments where daily life continues, different communities interact, and cultural transmission

gains continuity, serving as areas where tangible and intangible heritage values are intertwined. In this context, the preservation of historic markets cannot be limited to physical improvements at the building scale; the preservation process must be approached holistically, taking into account the forms of social organization, conditions of economic sustainability, and the multi-layered relationships that users establish with the space (UNESCO 2011; ICOMOS 2013).

When evaluating conservation practices carried out in historic urban areas in Türkiye, it is observed that “street revitalization” projects have become particularly widespread in recent years. These projects mostly focus on physical interventions such as facade renovations, material replacements, and public space improvements. However, the literature contains criticism that such practices do not sufficiently consider the multi-layered structure of historic areas and relegate social and cultural dimensions to a secondary position (Ahunbay 2011; Eraslan and Koç 2022). This situation necessitates a reassessment of street rehabilitation projects in the context of sustainable conservation.

The Historic Syriac Bazaar in Midyat district, the focus of this study, is one of the unique urban heritage sites reflecting Mardin’s multi-layered cultural structure. For centuries, the bazaar has been home to the production, trade, and social life practices of the Syriac community; with its stonework, traditional shop typologies, and craftsmanship activities, it constitutes an important component of the city’s cultural identity. Today, tourism-oriented transformation processes and street revitalization projects are leading to noticeable changes in the market’s spatial and social structure.

In this context, the study aims to evaluate the street revitalization practices carried out in the Historic Midyat Syriac Bazaar within the framework of a sustainable conservation approach. The research examines the effects of physical interventions in the bazaar on spatial integrity, cultural identity, and social sustainability from a multidimensional perspective, presenting a discussion based on the concepts of conservation-use balance and living heritage. Thus, the study aims to reveal the limitations of existing approaches to the conservation of historic bazaars and to contribute to holistic conservation strategies.

MATERIALS AND METHODS

This study is designed as a qualitative research aimed at evaluating the street rehabilitation interventions implemented in the Historic Midyat Syriac Bazaar within the context of sustainable conservation principles. During the research process, different data collection and analysis methods were used together to address the spatial, social, and cultural components of the bazaar, which is a multi-layered urban heritage area.

In the first phase of the research, a national and international literature review was conducted on sustainable conservation, historic markets, street revitalization practices, and the concept of historic urban landscapes. Within this scope, international conservation conventions and policy decisions published by UNESCO and ICOMOS were examined; academic studies on street rehabilitation projects implemented in historic urban fabrics in Türkiye were evaluated (UNESCO, 2011; ICOMOS, 2013; Ahunbay, 2011). The literature review provided a fundamental reference for establishing the theoretical framework of the study and for evaluating the current state of the Midyat Syriac Bazaar within this framework.

In the second phase, the historical development and spatial and architectural characteristics of the Syriac Bazaar were analyzed. Within the scope of this analysis, archival documents, old maps, plans, photographs, and written sources were used to reveal the transformation of the bazaar throughout its historical process. The spatial integrity of the bazaar was examined by evaluating its street fabric, building patterns, shop typologies, facade characteristics, and traditional building materials used. In this process, the current physical condition of the bazaar was addressed in the context of repair traces, functional changes, and spatial interventions.

Fieldwork constitutes an important part of the research. Within this scope, on-site observations were made in the study area, and the current state of the bazaar was documented using photographic documentation methods. During the observations, the patterns of use in the bazaar, pedestrian traffic, spatial densities, and uses of public spaces were evaluated. In addition, the effects of physical interventions carried out as part of street revitalization on the unique fabric of the bazaar were examined on site.

In the study, semi-structured interviews and survey studies were also used to outline the social and cultural dimensions of the bazaar. These studies were conducted with local merchants, users, Syriac citizens, and visitors; however, in line with the scope of the report, the data obtained was evaluated to reflect general trends rather than detailed statistical analyses. The interviews and

surveys conducted provided an opportunity to evaluate the daily usage patterns of the bazaar, traditional production processes, and perceptions regarding street revitalization initiatives.

Within the scope of this study, map-based evaluation methods were used to analyze the spatial structure of the bazaar. In this regard, functional distribution, facade character, and usage intensities were examined within a holistic framework; the effects of street revitalization applications on spatial continuity and spatial integrity were investigated. The data obtained were evaluated in a comparative perspective with similar historical market examples examined in the literature.

In the final stage, all data were subjected to a comprehensive assessment within the framework of a sustainable conservation approach. By analyzing the relationships between physical, social, and cultural components, the effects of street revitalization practices on the Historic Midyat Syriac Bazaar were revealed. This methodological approach ensured that the conservation strategies developed in the study's results and recommendations section were grounded in a theoretical and practical basis.

FINDINGS

This section discusses the findings regarding the spatial, functional, and socio-cultural impacts of street revitalization initiatives implemented in the Historic Midyat Syriac Bazaar. The findings have been interpreted within the framework of a sustainable conservation approach based on field studies, observations, visual documentation, and general assessments. Field studies show that street rehabilitation practices have improved the physical appearance of the bazaar to a certain extent. In particular, facade renovations, floor coverings, and infrastructure interventions have contributed to a more orderly and holistic spatial perception. Increasing the visibility of the traditional stone fabric stands out as a positive element that strengthens the legibility of the market's historical identity.

However, it has been observed that some applications are not fully compatible with the unique architectural character of the bazaar. The use of contemporary materials on the facades, the simplification of original details, and the standardization of some structural elements weaken the perception of the layered structure of the historical fabric. It has been determined that the street-level interventions were not addressed with a comprehensive planning approach covering the entire market fabric; instead, the interventions remained fragmented in places.

Following street revitalization initiatives, certain changes have occurred in the functional distribution of the bazaar. While some shops based on traditional craft production continue to operate, an increase in the number of commercial units geared toward tourism has been observed. Businesses such as souvenir shops, cafes, and restaurants have gained a more prominent place in the current economic structure of the bazaar. While this transformation can be seen as an element that increases the economic vitality of the bazaar, the decline of traditional production methods poses a risk in terms of cultural continuity. Functional changes have also affected the ways in which spaces are used; while some streets have seen increased traffic, areas where traditional production continues have seen a decline in use. This situation reveals that street revitalization efforts limited to physical improvements do not sufficiently consider functional and cultural balances.

The historic Midyat Syriac Bazaar has been not only a commercial center throughout history, but also an important venue for social interaction and cultural production. Field studies show that street rehabilitation practices have partially transformed the social use of the bazaar. Physical arrangements have increased the number of visitors to the bazaar; social use has become particularly noticeable during periods of intense tourist visits. However, this increase has only partially supported the relationship that local merchants and traditional user groups have established with the bazaar. As the visibility of Syriac artisans' production methods has decreased, the bazaar has tended to become more of a consumption-oriented space. This situation is considered a factor that weakens the bazaar's status as a living cultural heritage.

The findings indicate that the street revitalization projects implemented in the Historic Midyat Syriac Bazaar, while providing physical improvements, do not comprehensively address the principles of sustainable conservation. It is understood that the interventions are largely focused on visual arrangement and physical restoration, while the social structure, elements of intangible cultural heritage, and the participation of local actors in the process remain limited. When evaluated from a sustainable conservation perspective, it is evident that the bazaar is not merely a physical space that needs to be protected, but a living area where production, interaction, and cultural transmission continue. Therefore, it is necessary to re-evaluate the current street revitalization practices in a way that supports the multi-layered structure of the bazaar.

DISCUSSION

The findings of this study reveal that the street rehabilitation interventions carried out in the Historic Midyat Syriac Bazaar must be approached in a multidimensional manner from the perspective of sustainable conservation. The findings show that interventions in the bazaar have largely focused on physical improvements; however, social, cultural, and economic components have not been sufficiently integrated. This situation creates an important area of debate when compared to the fundamental principles of sustainable conservation in the literature.

Current conservation approaches emphasize that historic environments should be treated not only as physical entities but also as living social and cultural systems (Ahunbay, 2011; UNESCO, 2011). In this context, street revitalization practices that are limited to building facades and pavement arrangements are insufficient for preserving the multi-layered identity of historic bazaars. A similar situation was observed in the case of the Midyat Syriac Bazaar; although the interventions aimed at aesthetic improvement, it was seen that the mechanisms supporting the cultural production practices of the bazaar were limited.

The literature indicates that traditional bazaars are important carriers of urban memory and that interventions carried out in these areas are directly related to social memory (Kuban, 1993; Eldem, 1984). The street rehabilitation practices carried out in the Midyat Syriac Bazaar, while increasing spatial legibility, only reflect the visibility of the bazaar's historical layers and traditional craft production in daily life to a limited extent. This situation demonstrates that the cultural continuity of the bazaar cannot be ensured by physical protection alone.

Sustainable conservation literature defines the active participation of local communities and users in the process as a fundamental principle (ICOMOS, 2013). However, in the case of the Midyat Syriac Bazaar, it is evident that local merchants, and particularly Syriac artisans, were not sufficiently involved in the decision-making mechanisms during the street rehabilitation processes. This situation leads to the applications not fully aligning with local needs and the social impact of spatial interventions remaining weak.

Similarly, the impact of tourism on historic bazaars is a frequently discussed topic in the literature. It is noted that tourism-driven transformations, while providing economic vitality, can suppress traditional production methods and local life practices (Ashworth & Tunbridge, 2000; Yıldırım, 2020). In the Midyat Syriac Bazaar, the increase in tourist activities has led to traditional

crafts being pushed into the background, both spatially and functionally. This situation reveals that street revitalization practices do not sufficiently consider the balance between tourism and preservation.

The findings of the study show that street rehabilitation practices address the concept of preservation within a narrow framework of physical improvement. However, the concept of sustainable preservation aims to ensure the continuity of social relations, cultural practices, and economic structures along with the physical environment. In the case of the Midyat Syriac Bazaar, the weak relationship between these components is considered a factor that threatens the bazaar's status as a living cultural heritage.

In this context, it can be argued that the street rehabilitation projects carried out in the Historic Midyat Syriac Bazaar need to be re-evaluated within the framework of a comprehensive conservation strategy. Physical interventions must be carried out in conjunction with policies that support the social and cultural fabric of the bazaar, as this is a fundamental condition for sustainable conservation.

CONCLUSION AND RECOMMENDATIONS

This study aims to evaluate the spatial, social, and cultural impacts of interventions in the Midyat Syriac Historical Market within the framework of a sustainable conservation approach, by examining the street revitalization practices implemented there. The findings reveal that the conservation and improvement efforts carried out in the bazaar have largely focused on the physical environment; however, the multi-layered cultural structure of the area and its social and economic dynamics have not been sufficiently taken into account.

Historic bazaars are places that play an important role not only in their commercial functions but also in the formation of urban identity, the continuity of social memory, and the intergenerational transmission of cultural heritage (Kuban, 1993; Eldem, 1984). In this context, the Midyat Syriac Bazaar is one of the carriers of the city's historical identity with its Syriac community's tradition of craftsmanship, production culture, and spatial organization. However, the results of the study show that street revitalization practices mostly remain at the level of visual arrangement and physical renovation rather than supporting this unique identity.

UNESCO's Historic Urban Landscape (HUL) approach suggests that cultural heritage areas should be considered not only at the scale of buildings but also in conjunction with social relationships, cultural practices, and economic

processes (UNESCO, 2011). In the case of the Midyat Syriac Bazaar, however, it is evident that this holistic approach has not been sufficiently reflected in the implementation. While the physical environment improvements have enhanced the spatial perception, they have not been supported by social and cultural strategies that would strengthen the living cultural heritage character of the bazaar.

The assessments conducted within the scope of the study reveal that sustainable conservation cannot be achieved solely through interventions targeting the physical fabric; it is imperative that local users, particularly Syriac artisans and craftsmen, are actively involved in the process. ICOMOS' principles on cultural heritage management also define the participation of local communities in decision-making processes as one of the fundamental components of conservation (ICOMOS, 2013). In this context, the conservation and rehabilitation projects to be implemented in the Midyat Syriac Bazaar need to be reconsidered within the framework of a participatory management model.

Additionally, the effects of increased tourist activity in the market area on traditional craft production and the local economic structure should be carefully evaluated. The literature emphasizes that while tourism offers economic opportunities for cultural heritage sites, it can have a detrimental effect on local identity when it develops uncontrollably (Ashworth and Tunbridge, 2000; Yıldırım, 2020). Therefore, it is important that street revitalization practices are planned with an understanding that prioritizes cultural continuity rather than tourism-focused expectations.

Based on the results obtained from this study, the following recommendations can be developed:

- Street revitalization initiatives should not be limited to facade and pavement improvements; they should be approached with a comprehensive conservation strategy that supports the social and cultural fabric of the marketplace.
- In order to preserve and sustain the Syriac craftsmanship tradition, spatial and administrative policies that support the continuity of production spaces should be developed.
- Participatory protection models should be established to ensure the active participation of local businesses, users, and civil society organizations in the process.
- Planning and design decisions should be made with due consideration for the balance between tourism and conservation, ensuring that the unique character of the market is not compromised.

- Street beautification projects should be evaluated in line with long-term sustainability goals rather than short-term aesthetic improvements.

In conclusion, the street revitalization initiatives implemented in the Historic Midyat Syriac Bazaar present an important case study that warrants reconsideration from the perspective of a sustainable conservation approach. This study, through the findings obtained specifically in Midyat, offers a guiding assessment for other historic bazaar areas across Türkiye. The adoption of holistic conservation approaches that address physical, social, and cultural dimensions is considered a fundamental requirement for ensuring that historic bazaars can be passed on to future generations as living cultural heritage sites.

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CHAPTER 3

Industrial Heritage And Spatial Justice Inequality Through Creative Labor: A Comparative Reading Of Santralistanbul And Tate Modern

Rabia Çil¹

Abstract

This study examines the repurposing of industrial heritage sites along the axes of culture and creativity through a comparative analysis of Santralİstanbul, located in the Haliç area of Istanbul, and Tate Modern in London. While taking Richard Florida's creative class approach as an analytical starting point, the study questions this framework through Sharon Zukin's critiques of authenticity, cultural commodification, and publicness. The aim is to reveal how two transformation projects with similar industrial typologies produce diverging outcomes in terms of publicness, accessibility, and spatial justice under different institutional and governance regimes. In this context, Santralİstanbul's university-based, semi-public structure is compared with Tate Modern's institutionalized and symbolic public space, and the spatial effects of the creative economy discourse are critically discussed

Keywords: Industrial heritage, creative economy, publicness, authenticity, Santralİstanbul, Tate Modern

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Introduction: From Industrial Chimneys to Cultural Spaces

Reading these transformations not only through theoretical but also historical and architectural processes makes the actors behind the culture-focused repurposing of industrial heritage and its spatial outcomes visible. In this context, Santralİstanbul and Tate Modern offer two suitable examples for a comparative historical reading, both in terms of their historical origins and transformation processes.

Since the second half of the 20th century, the process of deindustrialization has led to the emergence of abandoned industrial areas in city centers; these areas have become key spaces for urban transformation strategies focused on culture, art, and creativity (Evans, 2005; Miles, 2005). The reuse of industrial heritage for cultural functions, on one hand, promises physical preservation and economic revitalization, while on the other hand, it brings debates around gentrification, selective publicness, and spatial inequality (Zukin, 2010; Smith, 1996).

This study addresses these tensions through the example of Santralİstanbul in the Haliç context and uses Tate Modern in London as a comparative reference case to deepen the analysis. The comparative approach does not aim to show an exact similarity between the two cases, but rather to discuss how similar industrial transformation logics produce divergent outcomes in publicness and spatial justice under different institutional, governance, and spatial contexts. Within this framework, the study aims to demonstrate how culture-based repurposing of industrial heritage can generate different spatial outcomes through the discourse of the creative economy, revealing that culture-driven urban transformations are not universal but context-sensitive processes.

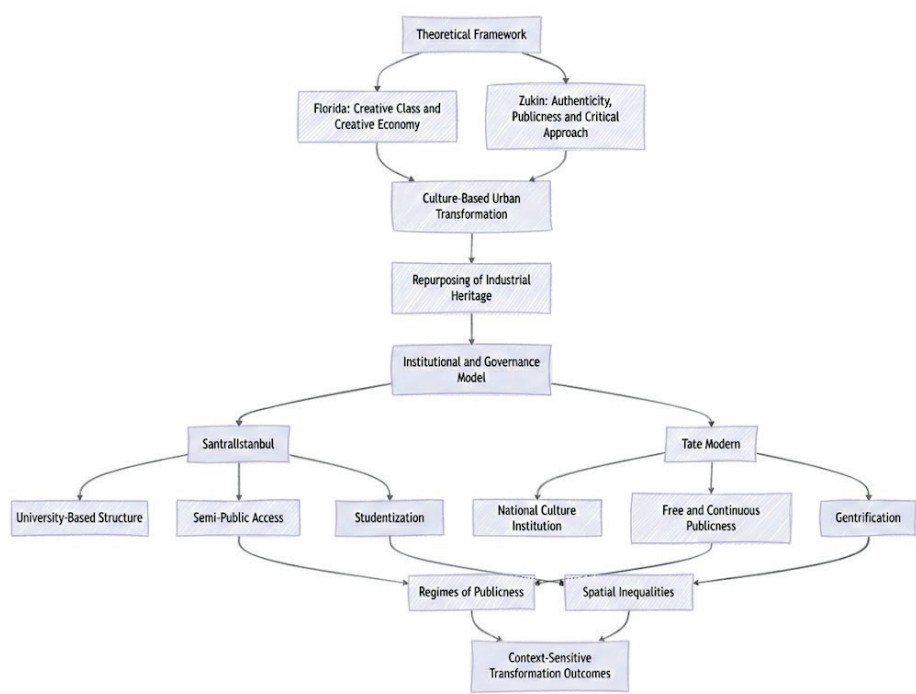
Theoretical Framework: Creative Class, Authenticity, and Critical Approaches

Richard Florida's creative class theory argues that sectors based on culture, art, knowledge, and innovation production bring economic dynamism to cities. According to Florida, universities, cultural institutions, and creative industries are key elements that attract skilled labor and enhance the competitiveness of cities (Florida, 2002). This approach has produced a powerful legitimizing discourse for culture-based urban transformation projects.

However, the creative class theory has been criticized for often relegating spatial inequalities, exclusion, and displacement processes to a secondary

position (Peck, 2005). At this point, Sharon Zukin’s concept of authenticity and her critical approach to culture-based urban transformation come into play. According to Zukin, culture is one of the main tools for producing authenticity in cities and commodifying the economic value of that authenticity (Zukin, 2010). The transformation of industrial heritage into cultural spaces preserves the material traces of the past while simultaneously generating new consumption patterns and selective publicness regimes. As can be seen in Figure 1, a diagrammatic reading of publicness and spatial justice comparisons can be made through the examples of Santralİstanbul and Tate Modern.

Figure 1. Comparative conceptual reading of Santralİstanbul and Tate Modern in terms of publicness and spatial justice



This study uses Florida’s creative class approach as an analytical framework and discusses its limitations through a critical perspective based on Zukin, using the examples of Santralİstanbul and Tate Modern.

Method

The research is based on a qualitative and comparative case study approach. Santralİstanbul is treated as the main case of the study, while Tate Modern is examined as a comparative reference case. The data set consists of academic literature, institutional reports, project publications, and secondary analyses (Evans, 2005; Tate, 2018; Bilgi University, 2010). The comparison is conducted through a qualitative and thematic reading in the context of the reproduction of creative labor, focusing on the institutional structures of both cases, public access regimes, the production of authenticity, and the post-transformation spatial effects.

Santralİstanbul: A University-Based Transformation

In this section, Santralİstanbul is examined as a university-based transformation model, and the process of repurposing industrial heritage for culture and education is analyzed within its historical context. The analysis aims to make visible the historical turning points that enabled the building's transition from industrial production to cultural and academic uses. Within this framework, the industrial origins and production process of the Silahtarağa Power Plant are first addressed.



FIGURE 1, URL-1

Historical Process and Industrial Origins

The Silahtarağa Power Plant began operating in 1911 as Istanbul's first large-scale electricity generation facility during the Ottoman Empire. Serving as the city's main energy provider until the 1950s, the building ceased production in 1983 due to technological obsolescence and changes in the city's energy infrastructure (Santralİstanbul, 2023).

Architectural Transformation and Repurposing

The transformation process carried out between 2004 and 2007 was led by Istanbul Bilgi University, with architectural firms such as Emre Arolat Architecture, Nevzat Sayın Architecture Services, and Han Tümertekin actively involved in the project. The restoration approach aimed to preserve the original spatial and structural character of the industrial heritage while integrating new cultural and educational functions within the existing building fabric (Arolat, 2007; Santralİstanbul, 2023).

Santralİstanbul, resulting from the conversion of the Silahtarağa Power Plant into a cultural and university campus, represents one of the most comprehensive examples of industrial heritage repurposing in Türkiye (Aksoy & Enlil, 2011). The project brings together a museum, exhibition spaces, and academic facilities, legitimized through the discourse of the creative economy.

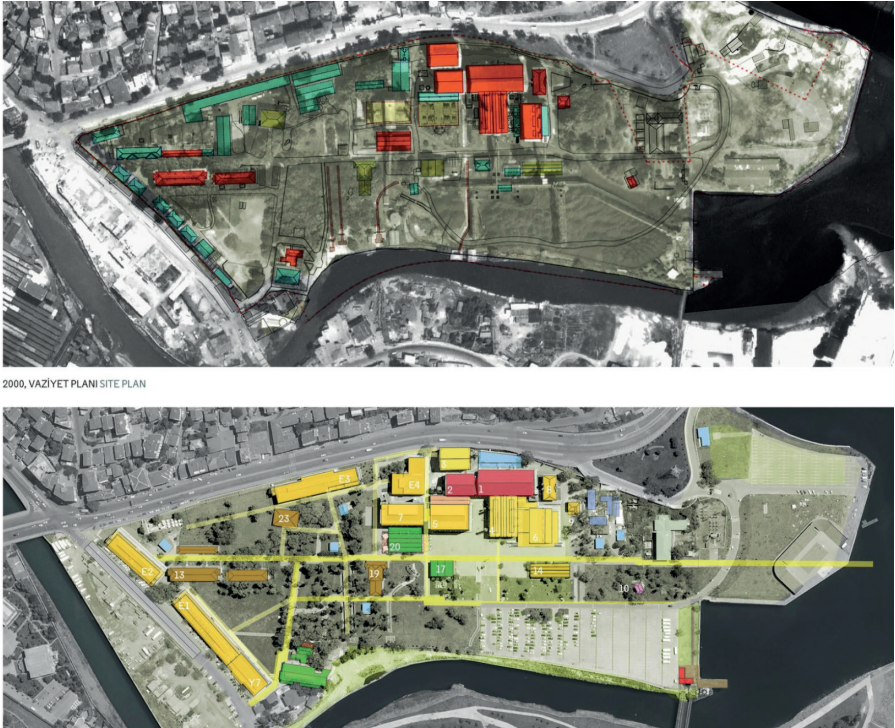


FIGURE 2, URL-2

However, the structuring of Santralİstanbul as a university campus has produced certain limits in terms of publicness. Although physically appearing accessible, the area possesses a semi-public character due to security regimes, the academic calendar, and institutional usage priorities (İnce, 2014). Additionally, the concentration of the student population has increased pressure on local housing, triggering studentification processes in the surrounding area (Çavuşoğlu & Strutz, 2014).

Table 1. Key Features of the Santralİstanbul Transformation

Feature	Description
Industrial function	Power plant
Year of conversion	2007
Institutional structure	University (Istanbul Bilgi University)
Main functions	Museum, exhibition areas, academic spaces
Level of publicness	Semi-public (temporally and institutionally limited)

This table can be used as an analytical tool to objectively summarize the transformation of Santralİstanbul along the axes of institutional structure and publicness, supporting the discussion. The project brings together a museum, exhibition spaces, and academic facilities, legitimized through the discourse of the creative economy.

Tate Modern: Transformation of Industrial Heritage into a Global Cultural Space

In this section, Tate Modern is examined as a global example demonstrating how industrial heritage has been repurposed within the framework of a nationally institutionalized cultural policy. The analysis aims to highlight the continuities and turning points between the building's industrial past and its cultural transformation. Accordingly, the historical process and industrial origins of the Bankside Power Station are first examined.



FIGURE 3, URL-3

The Bankside Power Station, designed by Sir Giles Gilbert Scott, served as a significant part of London's energy infrastructure between 1947 and 1963. After the plant was closed in 1981, it remained largely unused for a long period and was brought forward for cultural reuse in the early 1990s (Herzog & de Meuron, 2001).

Architectural Transformation and Cultural Reuse

The transformation process initiated by the Tate Gallery was carried out between 1995 and 2000 according to the project by Herzog & de Meuron architectural firm. The project preserved the monumental scale and material character of the industrial building, with the Turbine Hall, in particular, positioned at the center of public and exhibition uses (Evans, 2005; Herzog & de Meuron, 2001).

The conversion of London’s Bankside Power Station into Tate Modern is considered a globally recognized reference for the repurposing of industrial heritage through culture. Within the project developed by Herzog & de Meuron, the building’s architectural character was preserved while being transformed into a modern art museum, which opened to the public in 2000 (Herzog & de Meuron, 2001).

Tate Modern carries the quality of a symbolic public space through its policy of free permanent collections and high spatial permeability (Tate, 2018). However, the museum’s cultural attraction in the South Bank area has also produced gentrification effects, including increases in real estate values and transformations in the social fabric (Evans, 2005; Lees, Slater, & Wyly, 2008).

Table 2. *Key Features of the Tate Modern Transformation*

Feature	Description
Industrial function	Power plant
Year of conversion	2000
Institutional structure	National cultural institution (Tate)
Main functions	Exhibition areas, public indoor spaces
Level of publicness	High (continuous and free access)
Spatial impact	Gentrification and increase in real estate value

This table, when compared directly with Table 1 proposed for Santralİstanbul, allows for an analytical visualization of the institutional and spatial differences between the two transformations.

The conversion of London’s Bankside Power Station into Tate Modern is considered a globally recognized reference for the repurposing of industrial heritage through culture. Within the project developed by Herzog & de Meuron, the building’s architectural character was preserved while being transformed into a modern art museum, which opened to the public in 2000 (Herzog & de Meuron, 2001).

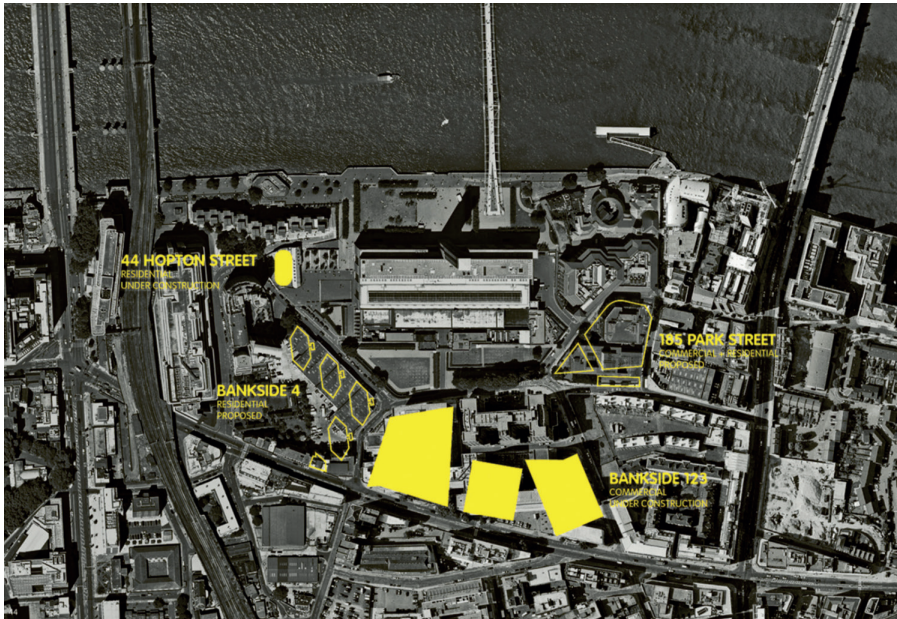


FIGURE 4, URL-4

Tate Modern possesses the quality of a symbolic public space through its policy of free permanent collections and high spatial permeability (Tate, 2018). However, the museum’s cultural attraction in the South Bank area has also produced gentrification effects, including increases in real estate values and transformations in the social fabric (Evans, 2005; Lees, Slater, & Wyly, 2008).

Comparative Reading: Santralİstanbul and Tate Modern

Timeline of Historical Transformation Processes

The timeline below presents a comparative chronological overview of the transition processes of Santralİstanbul and Tate Modern from industrial production to cultural use. This table makes visible how, despite having similar industrial origins, the two buildings have followed divergent transformation trajectories within different historical, institutional, and governance contexts.

Table 3. *Periodic Transformation Comparison of Santralİstanbul and Tate Modern*

Period / Stage	Santralİstanbul (Istanbul)	Tate Modern (London)
Industrial construction	1911–1914: Construction and commissioning of the Silahtarğa Power Plant	1947–1963: Construction of Bankside Power Station
Industrial use	1914–1983: One of Istanbul’s main electricity production centers	1963–1981: Part of London’s energy infrastructure
Closure / abandonment	1983: Termination of electricity production	1981: Closure of the power plant
Decision for adaptive reuse	2004: Decision to transform it into a culture and university campus	1994: Evaluation by Tate Gallery to be used as a museum
Architectural transformation	2004–2007: Restoration and reuse process (EAA, NSMH, H. Tümertekin)	1995–2000: Architectural transformation (Herzog & de Meuron)
Cultural opening	2007: Opening of Santralİstanbul	2000: Opening of Tate Modern
Post-conversion impact	University-based cultural focus, studentification, and limited publicness	Global cultural hub, gentrification, and tourism pressure

Note: *This table was prepared by the author using relevant academic and institutional sources, primarily Arolat (2007), Herzog & de Meuron (2001), Bilgi University (2010), Santralİstanbul (2023), and Tate (2018).*

This timeline demonstrates that the transformation projects are the result of not only physical interventions but also long-term historical and institutional processes. In the case of Santralİstanbul, the transformation was structured around university integration and cultural production, whereas at Tate Modern, the transformation was integrated with a nationally institutionalized cultural policy and the global art economy. This divergence forms the historical basis for the differences in publicness, authenticity, and spatial justice, which are discussed in the following subsections of the study.

This section does not aim to equate Santralİstanbul and Tate Modern directly, but rather to show how a similar logic of industrial heritage transformation produces divergent outcomes in different institutional, spatial, and governance contexts.

Institutional Structure and Governance

Santralİstanbul has been shaped by a university-based governance model, placing academic production and educational activities at the center of

the transformation. In contrast, Tate Modern operates within a nationally institutionalized museum structure, performing the function of exhibiting and circulating cultural production. This difference directly affects how publicness regimes are defined.

Publicness and Access Regimes

Tate Modern institutionally secures public access through its policy of free permanent collections. In Santralİstanbul, however, publicness has a more selective character due to the security regimes and usage priorities inherent to being a university campus. This demonstrates that publicness is determined more by governance choices than by physical openness.

Table 4. *Comparison of Public Accessibility Features of Santralİstanbul and Tate Modern*

Criterion (Ölçüt)	Santralİstanbul	Tate Modern
Institutional structure	University-based (Istanbul Bilgi University)	National cultural institution (Tate)
Public access status	Semi-public	Public
Physical access	Generally open to the area; within campus boundaries	Constantly open, high spatial permeability
Temporal access	Limited by academic calendar, events, and security regimes	Regular year-round, within museum hours
Pricing policy	Variable depending on the museum and events	Permanent collections are free
User profile	Students, academics, limited visitor audience	Broad public user profile, tourists, and local people
Quality of publicness	Selectively and institutionally framed	Institutionally guaranteed
Spatial impact after transformation	Studentification and limited public use	Gentrification and tourism pressure

Note: *The table was prepared by the author using relevant literature on Santralİstanbul and Tate Modern (Evans, 2005; Zukin, 2010; Aksoy & Enlil, 2011; İnce, 2014; Lees et al., 2008; Tate, 2018).*

Authenticity and Cultural Commodification

Zukin's (2010) concept of authenticity points to the reinterpretation of the material and symbolic traces of the past in culture-based urban transformations, using them to generate economic and cultural value. In the case of Tate Modern, authenticity becomes visible and exhibit-able through the preservation of the industrial heritage's architectural scale and spatial character. Spaces such as the Turbine Hall allow the industrial past to be directly experienced, while this historical narrative is integrated with the global art market and cultural consumption practices. This demonstrates that authenticity provides a public experiential space while simultaneously being circulated through processes of cultural commodification (Evans, 2005; Zukin, 2010).

In Santralİstanbul, however, the production of authenticity occurs more implicitly within an institutional framework. While the physical traces of industrial heritage are preserved, their meaning is reconstructed through academic production, exhibitions, and university-based cultural activities. This results in authenticity being produced not as an open object of consumption but as a form of selective cultural capital targeting a specific user group. The cultural commodification process emphasized by Zukin (2010) operates in a more limited and indirect manner at Santralİstanbul, and when considered alongside publicness and access regimes, it creates a spatial arrangement where authenticity is not experienced equally by all.

Spatial Inequalities and Justice

The spatial transformation observed around Santralİstanbul is shaped more by studentification dynamics than by classic gentrification processes. The university-based transformation model has attracted a dense student and academic population to the area, increasing housing demand; this has led to rising rents and heightened vulnerability in local residents' living conditions. As emphasized by Çavuşoğlu and Strutz (2014), although studentification processes differ from large-scale capital-driven gentrification, they ultimately produce a similarly selective social structure over time. In this context, while Santralİstanbul functions as a public and cultural focal point, it has not completely eliminated surrounding spatial injustices; on the contrary, it has laid the groundwork for new forms of inequality along the axis of university integration.

In the area surrounding Tate Modern, the transformation is associated with a larger-scale, market-driven gentrification process. As noted by Evans (2005) and Lees, Slater, and Wyly (2008), the museum's emergence as a global cultural

attraction in the South Bank region has caused rapid increases in real estate values, restructuring of the housing market, and displacement of low-income groups. Tate Modern's high level of public accessibility has not mitigated the inequalities produced by this spatial transformation; rather, it has made the tension between publicness and spatial justice visible. This comparison demonstrates that, although culture-based urban transformations can enhance public access, they can produce context-sensitive and contradictory outcomes in terms of spatial justice.

Discussion and Conclusion

The comparative analysis shows that culture-based urban transformation projects do not automatically produce universal or inclusive outcomes. The Santralİstanbul case demonstrates that, although university-based transformations can stimulate the production of creative labor, they can also generate vulnerabilities in terms of publicness and spatial justice. Tate Modern, on the other hand, offers a more inclusive model of public access but cannot completely eliminate the risks of gentrification and economic exclusion.

These findings indicate that Florida's (2002) creative class approach alone is insufficient and must be considered alongside Zukin's (2010) critiques of authenticity and cultural commodification. Culture-based transformation projects reproduce not only physical spaces but also publicness and access regimes (Harvey, 1989; Graham & Marvin, 2001).

In this context, the study argues that planning policies should address cultural investments not as isolated projects but in an integrated manner with housing, transportation, and public space policies. The examples of Santralİstanbul and Tate Modern make visible both the potentials and limitations of culture-based transformations under different institutional models, providing a critical comparative basis for future research and planning practices.

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CHAPTER 4

Capillary Moisture In Historical Masonry Structures: Damage, Diagnosis And Technology

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Abstract

The presence of water in historic masonry structures is a critical issue in terms of both structural health and user comfort. Water ingress into the structure and the emergence of moisture problems occurs through a series of sequential processes. This study examines the phenomenon of capillary moisture (rising damp) in historic masonry structures within the framework of its formation mechanism, damage processes, diagnosis and monitoring methods. It has been established that capillary moisture is transported from the ground into the wall structure through capillary forces in porous building materials; material properties, ground conditions, climate data and user behaviour play a decisive role in this process. The movement of moisture within the structure has been evaluated through the stages of water ingress, storage, and evaporation. Furthermore, it has been emphasised that superficial interventions do not permanently resolve the issue, that incorrect applications can exacerbate the damage, and that accurate diagnosis is critical for effective protection.

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Water and Material Interaction in Masonry Structures

The presence of water within structures is an important issue. Water can naturally exist in three different states within building materials: solid, liquid and gas (Künzel, 1995). Many building materials contain a certain amount of water before and after the construction process; however, this does not always lead to harmful consequences. The problem arises when the amount of water in the material exceeds a certain level.

The structure involves processes of water inflow and outflow that create a balance under normal conditions. However, excessive moisture means water accumulation within the structure and a disruption of this balance. For this to occur, water must enter the structure from outside. The main sources of excessive moisture are rainwater, groundwater and condensation. In addition, leaks, water leaks, misuse and various user-related factors can also cause moisture formation (Smith, 1984). Water ingress into the structure can generally be classified as air zone (precipitation, indoor-outdoor air humidity, condensation, etc.), air-ground (splashing water), and ground zone (ground moisture, seepage water, etc.) (Erten, 1996).

Condensation occurs when the surface temperature of a building element is equal to or lower than the dew point of the air it comes into contact with, causing water vapour in the air to turn into liquid and leading to moisture accumulation on the building element. This phenomenon is also known as surface condensation. It can occur on internal and external walls depending on usage conditions or climatic effects. Particularly in indoor spaces, if there is insufficient ventilation, the water formed as a result of condensation can accumulate on the wall, causing dampness and damage (Erten, 1996; Smith, 1984).

Rainwater penetrates the building material and evaporates under the sun's influence during dry periods. In this way, water moves within a cycle of wetting and drying. On the other hand, rain carried by strong winds can slow down the drying cycle by pushing moisture, especially if there are gaps between joints, into the depths of cracks. In areas with high rainfall and wind, rainwater can penetrate the structure. Considering factors such as wind direction and the orientation of the structure, intense wetting may occur on one or two sides of the structure (Smith, 1984).

However, rainwater can accumulate on hard surfaces around the building and splash onto the structure. This phenomenon, known as splashback, occurs in the air-ground contact zone (Erten, 1996).

The structure is exposed to ground moisture, pressurised and unpressurised water from the ground level (Erten, 1996). Groundwater is generally found a few metres below the surface and may rise and fall depending on seasonal changes and urban conditions. Damaged drainage pipes and seepage water can cause similar situations. In such cases, moisture penetrates the structure both horizontally and vertically, causing various types of damage. As moisture rises, evaporation occurs from the exposed surfaces of the structure's walls, and the water entering and leaving the structure reaches a certain level of equilibrium. Gravity limits this vertical progression. This mechanism is called rising damp (Smith, 1984).

Another factor is user-related problems. Poorly designed drains, leaks from damaged pipes and faulty equipment can cause dampness in walls. In addition, faulty coatings and paints can prevent moisture from escaping from the wall, creating a constant state of dampness (Smith, 1984). Therefore, identifying sources of moisture is crucial for understanding and solving moisture problems.

Hygrothermal Behavior of Historical Structures

Historic masonry structures are building systems that have been exposed to varying climatic conditions over centuries and are largely composed of natural materials. These structures, made of porous materials such as stone, brick and mortar, are in constant interaction with environmental factors such as water and temperature (Kuzuimamlar, 1995).

The hygrothermal behaviour of historic masonry structures is explained by jointly evaluating the heat and moisture transfer processes occurring within the porous structure of building materials. Building materials exhibit hygroscopic and non-hygroscopic properties. Hygroscopic materials absorb moisture from the environment until they reach a certain water content and equilibrium is achieved, while non-hygroscopic materials remain largely dry. Hygroscopic building materials can store moisture within themselves and release it back into the environment when conditions are right. This property enables the structure to adapt to short-term environmental changes. However, long-term moisture accumulation leads to material deterioration (Künzel, 1995).

The storage and transport of moisture within a structure depends on many factors, such as the porosity, permeability, wettability and salt content of the material. A building material has the potential to absorb moisture until its pores

are completely filled with water; however, the actual amount of moisture it can retain is largely dependent on the relative humidity of the environment. Moisture storage in building materials can be classified into the hygroscopic zone, capillary zone, and saturation zone (Künzel, 1995).

Table 1. Schematic classification of the moisture storage function of a hygroscopic material

Area	Definition	Explanation
A	Dry state - Sorption zone	This is the low humidity range where moisture transport occurs primarily through water vapor diffusion.
B	Sorption zone - Capillary water zone	This is the medium-to-high humidity range where moisture transport is predominantly via capillary water conduction.
C	Capillary water zone - Supersaturated zone	It is a very high humidity range where the pores are largely filled with water.

In region A, the material absorbs moisture from the air and reaches equilibrium moisture content. The amount of moisture is defined by sorption isotherms. In region B, water is drawn into the material by capillary action. Moisture transport occurs in the liquid phase. In region C, the material reaches near saturation with free water; there is no equilibrium state (Künzel, 1995).

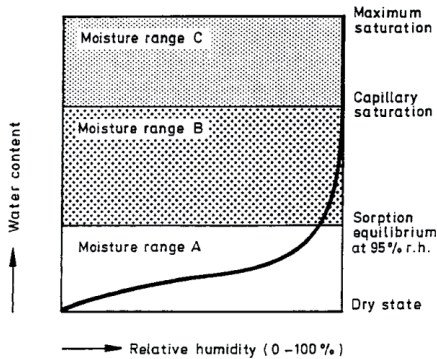


Figure 1. Schematic classification of the moisture storage function of a hygroscopic material (Künzel, 1995).

Historical buildings have higher vapour permeability compared to modern buildings. The orientation, thickness and material properties of building elements determine their hygrothermal performance, and incorrect interventions can also disrupt this natural balance.

Pore Structure and Diffusion Capacity of Masonry Material

Masonry building materials have a structure consisting of numerous micro and macro pores. The percentage ratio of a material's pore volume to its total volume is defined as 'porosity'. The pore structure determines the material's water absorption and transmission capacity. The interconnectedness, arrangement, and size of the pores are related to 'permeability'. The higher the permeability of a material, the greater its potential for moisture transmission (Smith, 1984).

The filling of a material's pores with water can be defined as 'water absorption (absorption)'. Water absorption capacity is determined by the percentage of absorbed water relative to the material. The uptake of moisture from the air by a hygroscopic material is referred to as 'hygroscopic absorbency'. Water absorbed by sorption adheres more strongly than water absorbed by absorption. In this way, depending on factors such as the structure of the material and the properties of the air, the moisture retained within the material as it absorbs and releases moisture is defined as 'hydric equilibrium moisture content' (Kuzuimamlar, 1995).

Moisture transport in porous building materials essentially occurs through capillary transport and diffusion (Künzel, 1995).

Table 2. *Moisture transport mechanisms*

Moisture Transport Mechanism	Explanation
Capillary Convection	It is the attraction of water through capillary forces in porous materials.
Surface Diffusion	It is the movement of adsorbed water layers on pore walls due to differences in relative humidity or suction tension.
Vapor Diffusion	resistance is the movement of water vapor due to a pressure difference. It is expressed by the diffusion resistance coefficient (μ).
Moisture Transport in Polymers	Water transport in polymer coatings and membranes occurs not through the pores of the material, but by dissolving into the polymer chains.
In the Oversaturation Zone Moisture Convection	If the material is completely saturated with water, moisture movement can occur through gravity, vapor diffusion, or pressure differences.
In case of freezing Moisture Convection	When the temperature drops below 0°C, water in large pores freezes, but limited moisture movement can continue in small pores where liquid water remains.

When the material comes into contact with liquid water, capillary forces draw the water into the pores, causing moisture to migrate within the material; this process is particularly significant in the lower sections of walls and on surfaces wet by rain (Hall and Hoff, 2021). In contrast, under lower humidity conditions, water moves by diffusion due to vapour pressure differences formed in the pores, and this process plays an important role in the drying behaviour of building elements (Hall and Hoff, 2021; Künzle, 1995). Evaporation occurring on building surfaces is one of the primary boundary conditions determining moisture distribution within the material and is generally accepted as the fundamental mechanism directing moisture flow within walls (Hall and Hoff, 2021).

The Importance of Moisture Control in the Context of Sustainable Conservation

Moisture is one of the most common causes of deterioration observed in historic buildings. Uncontrolled moisture leads to various physical, chemical, biological, and structural damage. It can also negatively affect compressive and shear strength, thereby reducing the mechanical performance of the wall (Franzoni, 2014).

In porous materials, the thermal conductivity coefficient (U-value) is low and water absorption capacity is high, so when the material becomes wet, it loses much of its insulating properties, causing heat loss. This means increased energy consumption. Moisture also promotes the growth of mould and microorganisms, creating unfavourable indoor conditions. This poses a risk to both the structure and the health of its occupants (Kuzuimamlar, 1995).

In conservation work, it is essential to correctly diagnose the source of moisture. Incorrect interventions can exacerbate the problem. Vapour-impermeable coatings can cause moisture to become trapped within the structure. Sustainable conservation approaches aim to preserve the natural moisture balance of structures. Therefore, attention must be paid to the suitability of the systems to be used (Franzoni, 2014).

Capillary Rise Mechanism: Theoretical Framework

Capillary Absorption and Surface Tension Physics

There is no single solution that covers all types of climate, geographical features and structural characteristics. Due to factors such as climate and geography, building materials and water saturation levels, structures should

be addressed with a holistic approach specific to the building rather than individual interventions. (Franzoni, 2014)

Moisture transport in porous building materials is a complex phenomenon. To understand this situation, it is necessary to understand various concepts and their functioning.

A membrane-like force is observed on the surface of a free-flowing liquid, and this force is called 'surface tension'. While the molecules inside the liquid attract each other in all directions, the molecules at the surface have a different equilibrium state due to the attractive forces between themselves, and this situation causes surface tension to occur (Kuzuimamlar, 1995).

Wettability is possible when the adhesion force between the liquid and the solid surface is greater than the cohesion force between the liquid molecules. If the surface is 'wetable', adhesion occurs between the water and the surface, and the water spreads over the surface, becoming convex. Conversely, when adhesion is insufficient, water cannot adhere to the surface and retains its concave form. This behaviour may vary depending on the properties of the liquid and solid material (Kuzuimamlar, 1995).

Capillarity is the phenomenon arising from the adhesion forces between water and a surface being greater than the cohesion forces within the water itself. Water seeks to advance along the surface it contacts but cannot overcome the surface tension, thus rising by following the water molecules it contacts (Smith, 1984). It is fundamentally based on Jurin's law (Franzoni, 2014).

Jurin's Law and Factors Affecting Rise Height

The capillary absorption of water in porous materials is a complex, multi-phase process dependent on pore size, surface tension, and water viscosity (Franzoni, 2014; Kuzuimamlar, 1995). This process occurs under the combined effect of different driving forces. With capillary water transport, water can move upwards in narrow pores. This phenomenon was first studied by Pierre-Simon Laplace and later expressed in a formula by James Jurin. According to Jurin's law, the height to which water rises depends on surface tension, contact angle, liquid density, gravity, and capillary radius (Franzoni, 2014).

$$h = (2\tau \cos \theta) / (\rho g r)$$

Figure 2. Water level rise (h) according to Jurin's law (Franzoni, 2014).

Here, h is the height of the water rise, θ is the contact angle between water and capillary surfaces, ρ is the liquid density, τ is the surface tension, and g is the gravitational acceleration. For wettable materials such as brick and stone

(when the contact angle is approximately zero), Jurin's law can be simplified as $h \approx 15 / r$ (where h is in metres and r is in micrometres) (Franzoni, 2014).

The level that separates the damp, dark area from the dry area in masonry walls and indicates the maximum height that water can reach is called the 'equilibrium line'. In real walls, due to the complex structure of the pores and the evaporation occurring on the surface, the height reached by the water is much lower than the level in an ideal capillary tube. Therefore, despite the existence of an almost stable 'equilibrium line' in masonry walls, equilibrium is not static but a continuously ongoing dynamic process (Franzoni, 2014).

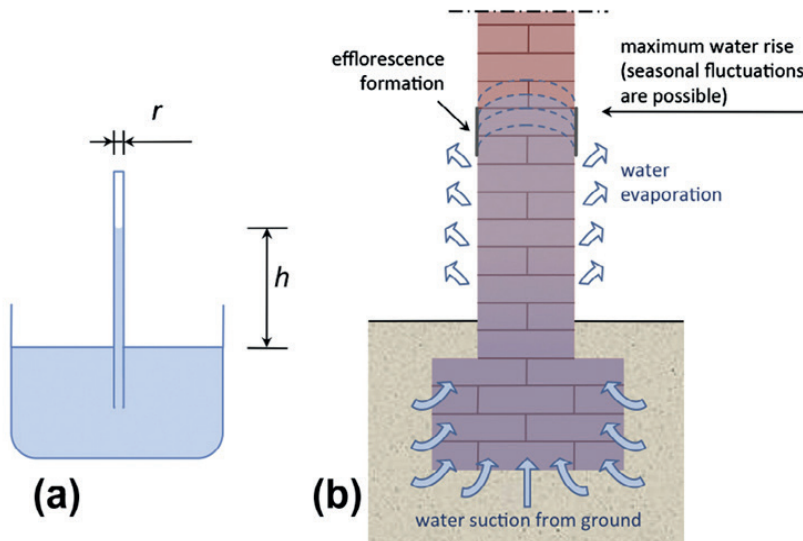


Figure 3. (a) The height (h) of water in an ideal capillary tube with radius r ; (b) Schematic representation of capillary rise of water in masonry structures (Franzoni, 2014).

Factors such as the groundwater level, climatic conditions and ventilation can cause this height to vary seasonally. Furthermore, covering the wall surface with waterproof materials does not usually solve the problem; on the contrary, it can cause the water to rise higher. Therefore, solutions are generally based on the principles of reducing water ingress or decreasing the wall's water absorption capacity (Franzoni, 2014).

The Hydrological Connection Between Groundwater and Structural Elements

Rising damp is defined as the capillary action of water rising from the ground beneath the building's foundations, from soil adjacent to the wall, or from surface water accumulation into the building walls. This phenomenon occurs as a natural part of the capillary action and evaporation cycle discussed in the preceding sections (Hall and Hoff, 2021).

Walls generally extend to a certain level below ground level. Consequently, they are in contact with wet ground. Walls typically have finer pores than the ground they stand on, enabling them to draw water from the soil. This situation can cause significant damage, particularly in historic masonry structures (Hall and Hoff, 2021). The movement of moisture is related to temperature and humidity values, sunlight, the presence of salts, the porous structure of building materials, wall thickness, and material layers (De Oliveira, Mesquita, de Oliveira Freire, Bertini, 2023; Hall and Hoff, 2021).

Moisture moves from warm areas to cold areas and from environments with low salt concentration to those with high salt concentration within a porous structure, depending on temperature and concentration differences (Smith, 1986). In situations where there is no insulation between the wall and the floor, or where the insulation is damaged, ground water can penetrate the wall. The absence of water loss through evaporation supports the storage of this moisture in the wall, and together with the water, it reaches a certain equilibrium within the wall structure (Hall and Hoff, 2021). Fluctuations are possible at this equilibrium line, which separates the damp area from the dry area, due to factors such as climatic conditions, ventilation conditions, and the processes created by the entry and exit of water (Franzoni, 2014; Hall and Hoff, 2021).

According to Hall and Hoff (2021), the capillary rise height (h_{ss}) in equilibrium is directly proportional to the square root of the wall thickness (b) and inversely proportional to the square root of the microenvironmental evaporation rate. Therefore, an increase in wall thickness (along with the prolongation of the process) implies an increase in capillary moisture height (De Oliveira et al., 2023; Hall and Hoff, 2021). As the water absorption area (inner region) increases, the lateral area (evaporation region) remains constant; therefore, evaporation remains limited by the surface area relative to the thickness. As the internal volume increases, more water can be stored. Evaporation loss becomes relatively less effective. Therefore, equilibrium is established at a higher level (De Oliveira et al., 2023; Hall and Hoff, 2021).

$$h_{ss} = S \left(\frac{b}{N e f_e} \right)^{1/2}$$

Figure 4. Water level rise by Hall and Hoff (Hall and Hoff, 2021).

N represents the number of surfaces open to evaporation (1 or 2), e is the micro environmental evaporation rate, f_e is the water content of the wet zone, and b is the wall thickness (Hall and Hoff, 2021).

De Oliveira et al. (2023) state that the effect of mortar thickness on rising damp is negligible due to its limited volumetric contribution relative to the total wall volume. In contrast, it is emphasized that the composition of the mortar, particularly when cementitious mortars are used, significantly affects the rising damp mechanism by increasing capillary water transport. The presence of salt, increases capillary moisture height (De Oliveira et al., 2023).



Figure 5. Ani Ebul Manuçehr Mosque (Kars), Mustafa Bey Bathhouse (Amasya), Mümüne Hatun Mausoleum (Nakhchivan) (Author archive)

Damage: Structural and Material Deterioration Caused by Capillary Moisture

The physical, chemical, biological and structural damage caused by capillary moisture in historical masonry structures, as determined in accordance with the literature, is presented in the table below.

Table 3. *Types of damage caused by capillary moisture in historical masonry buildings*

Damage	Name of Damage	Explanation
Physically	Freeze-Thaw	Expansion and cracking of the material due to the freezing and thawing of moisture inside the wall
	Moisture	Bubbling and flaking of plaster or paint due to moisture
	Vapor diffusion barrier	Prevention of water vapour escape
Chemical	Salinization (Efflorescence-subflorescence)	Dissolved salts within the wall rising to the surface and crystallising, creating chemical stress
	Material degradation	Weakening of mortar and bricks due to moisture
	Sulfate attack	Sulphate ions react with mortar or brick, causing crystals to expand and damage the material
Biological	Mold	Proliferation of microorganisms, black-green stains and odour formation
	Bacterial degradation	Bacterial effects on damp walls or plaster surfaces, causing discolouration and odour formation
	Lichen/Moss formation	Microbial growth on damp and shaded surfaces, green-brown stains and slipperiness
Structural	Joint damage	Loss of mechanical strength in mortar or brick joints
	Loss of mechanical strength	Structural weakening of the wall's load-bearing capacity
	Structural deformation	Deformation of materials due to prolonged moisture accumulation

Diagnosis: Identification and Analysis of Moisture Sources

The table below shows the sources of capillary moisture in historic masonry structures and the effect of the movement of moisture within the structure on rising damp.

Table 4. Capillary moisture sources and rising damp (↑ increases, ↓ decreases, + positive, - negative)

Moisture source	Parameter	Penetration	Storage	Exit	Rising Damp
Structure	Fine pores	↑↑	+	–	High
	Connected pore	↑↑	+	–	High
	Joints and cracks	↑	+	–	Middle
	Wall thickness	–	+	–	Middle
	Surface area	–	–	↑	Low
Ground	Groundwater	↑↑	+	–	High
	Salt presence	↑↑	+	–	High
	Permeable soil	↑↑	+	–	High
Climate	Temperature	–	–	↑↑	Low
	Relative humidity	↑	+	↓	High
	Precipitation	↑	+	–	Middle
	Wind				Low
	Evaporation	–	–	↑	Low
User	Impermeable coating	–	+	–	High
	Inadequate floor insulation.	↑↑	–	–	High
	Inadequate ventilation				High
	Inadequate drainage	↑↑	+	–	High
	Improper use	↑	+	–	High

Technology: Contemporary Measurement and Monitoring Systems

Various methods are available for monitoring capillary moisture in historic masonry structures. Direct methods rely on the physical or chemical removal of water from the sample. Indirect methods rely on measuring physical properties that change in response to changes in water content and require calibration (e.g., Karl Fischer titration, GPR – Ground Penetrating Radar, Neutron Radiography, Gamma Ray Backscatter, X-ray/CT, NMR, Single-Side NMR, MRI, PET, etc.). Below, traditional and innovative methods used to detect capillary moisture content and damage in historic masonry structures are presented in a table, comparing their suitability for historic structures, advantages, and disadvantages (Hall and Hoff, 2021).

Table 5. *Traditional methods used in capillary moisture measurement*

Method / Tool	Advantage	Disadvantage	Suitability
Gravimetric Method	Reference method	It damages the structure.	Low
Salt Analysis (Ion Analysis)	Identifying the source of moisture.	A laboratory is required.	Middle
Carbide (CM) Method	Applicable in the field.	A sample is needed.	Middle
Capacitive RH sensor	Rapid moisture estimation.	A hole is needed.	Middle
Thermal Probe	Indirect humidity estimation	A hole is needed.	Middle
Resistance type RH sensor	Fast and practical	It is affected by salt.	High
AC Impedance / Spectroscopy	Detailed analysis	Calibration is required.	High
Electrical Resistance Tomography	Area mapping	Difficult to interpret.	Poor
Microwave Humidity Meter	Provides in-depth measurement.	Costly	Poor
Electromagnetic Conductivity	Large area scanning	Sensitivity is limited.	Poor
Visual Inspection	Initial diagnosis	Not quantitative	Very High

**Figure 6.** Infrared Thermography (EuroLab, n.d.), Hygrometer (Trotec Australia, n.d.).

Table 6. Innovative methods used in capillary moisture measurement

Method	Advantage	Disadvantage	Suitability
WUFI	Time-dependent hygrothermal simulation	Dependent on correct input data.	Very high
Delphin	2D/3D multilayer modeling	Complex interface	High
Infrared Thermography	Early detection	Limited by surface temperature.	Very High
Long-Term Data Logging (Datalogger)	Long-term monitoring	Collecting data takes time.	Very high
TDR (Time Domain Reflectometry)	Sensitive, long-term monitoring capability, data via embedded sensor.	It's costly and requires expertise.	Middle
AI + IR Thermography	Automatic, precise humidity detection.	New technology, limited field application.	Middle
Digital Twin Approach	Real-time monitoring + forecasting	It requires data infrastructure and software.	High

Conclusions and Future Projections

Rising damp in historical masonry structures is not merely an aesthetic concern but a dynamic deterioration process that directly threatens structural longevity and user comfort. This study has comprehensively examined the mechanisms of capillary moisture, material-based interactions, and contemporary diagnostic technologies. The primary findings of the research are summarized as follows:

Diagnosis and Data-Driven Approach: A fundamental error in combating rising damp is the application of superficial interventions without addressing the root source. For an effective preservation strategy, the moisture transport mechanism—encompassing the stages of absorption, storage, and evaporation—must be precisely mapped using Non-Destructive Testing (NDT) methods.

Technological Transformation and Monitoring: Traditional moisture measurement techniques are increasingly being replaced by Infrared Thermography (IRT), microwave sensors, and Internet of Things (IoT)-based continuous monitoring systems. In particular, Artificial Intelligence (AI)-supported data analysis and Digital Twin modeling have emerged as critical tools for predicting moisture movement and establishing proactive risk management models.

The Role of Hygrothermal Simulation: Utilizing simulations such as WUFI, which account for the pore structure of building materials and site-specific environmental conditions (climatic data, groundwater levels, etc.), is essential to minimize the risk of incompatible interventions before final restoration decisions are made.

Holistic Preservation: The challenge of capillary moisture cannot be resolved through isolated methods, such as chemical injection or drainage alone. Instead, adaptive solution models must be developed by integrating material properties, soil conditions, and user behavior into a unified strategy.

In conclusion, the principle of “accurate diagnosis, smart monitoring, and minimum intervention” must be adopted to ensure the sustainable transmission of historical structures to future generations. This study demonstrates that the integration of advanced technological tools into the restoration discipline is no longer optional but a fundamental necessity for the preservation of cultural heritage.

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CHAPTER 5

Nd:Yag Laser Cleaning In The Conservation Of Stone Cultural Heritage: International Case Studies

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Abstract

Stone artifacts constitute a large portion of cultural heritage. These artifacts play a crucial role in understanding the period and society to which they belong. However, due to various environmental, physical, and chemical factors, deterioration occurs over time on the surfaces of these stone artifacts. The controlled cleaning and removal of these deteriorations is essential for ensuring the continued physical preservation of the objects. One of the methods used for this purpose is laser cleaning.

In recent years, in the preservation of stone cultural heritage, particularly as an innovative method that enables the selective and controlled removal of dirt, black crust, and biofilm layers from the surface. This study examines the current literature on Nd:YAG laser cleaning, evaluating the system's operating principles, technical characteristics, effectiveness on different types of stone and deterioration, and application parameters. The literature shows that Nd:YAG laser applications carried out with appropriate parameters provide high

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selectivity and controlled cleaning on stone surfaces, with minimal physical impact. However, it has been observed that the selection of incorrect parameters can lead to undesirable effects, especially discoloration. In conclusion, while Nd:YAG laser cleaning is an effective and reliable method for preserving stone artifacts, it is crucial to select appropriate parameters in each application, taking into account various factors such as the type of stone, the type of deterioration, and the layers of the surface that need to be preserved.

Keywords: Laser cleaning, Nd:YAG, deterioration of stone artifacts, conservation studies

Introduction

Natural stone, as one of the oldest and most widely used materials in human history, holds an important place in the cultural heritage of different civilizations. Thanks to its durability, abundance in nature, and variety of colors, textures, and patterns, stone has stood out as both a functional and aesthetic material. Throughout history, natural stones have been preferred first for hunting, then for building elements, cladding materials, decorative components, and in monumental structures (Angı et al., 2023, p.17; Aykaç Selamoğlu, p.47). Natural stones play a significant role in understanding the technical, cultural, and artistic characteristics of the period to which they belong (Özkan, 2022, p.13; Aykaç Selamoğlu, 2025, p.47).

Although natural stones are durable materials with high strength, they are subject to deterioration over time due to various factors (Yardımlı & Dal, 2021, p.429; Aykaç Selamoğlu, 2025, p.47). This deterioration occurs due to various environmental, chemical, biological, and anthropogenic factors (Zakar & Eyüpgiller, 2020, p.108; Aykaç Selamoğlu, 2025, p.47). In particular, air pollution, acid rain, biological colonization, salt crystallization, and inappropriate repairs lead to the formation of crusts, biofilm layers, deposits, and surface soiling on stone surfaces, which in turn negatively affect the physical and chemical durability of the stone. Therefore, surface cleaning is considered one of the most critical stages in the conservation of stone materials. The extent to which deterioration such as dirt and crust formation can be eliminated during the cleaning process is one of the most important issues (Zakar & Eyüpgiller, 2020, p.117; Aykaç Selamoğlu, 2025, p.47).

Previous knowledge on cleaning methods has been reevaluated in recent years, leading to significant developments (Ersen, 2013, p.6). One of the most prominent developments is the application of laser cleaning applications. Among these, the most widely used systems are Nd:YAG lasers, which are solid-state laser systems.

The main aim of this study is to evaluate laser cleaning methods used in the conservation of stone cultural heritage within the framework of Nd:YAG laser technology through different application examples. By examining case studies presented in the literature, the effectiveness of Nd:YAG lasers on stone surfaces, their advantages and limitations, as well as the parameters that must be considered during application are assessed. In this way, the study aims to present the current body of knowledge on the use of laser cleaning for stone surfaces and to provide a guiding framework for selecting appropriate methods in future conservation applications.

Major Deteriorations Requiring Cleaning on Stone Surfaces

Crust

These are generally consistent, strong, and compact accumulations of material occur on stone surfaces. Their morphological characteristics, color, and physical, chemical, and mineralogical compositions are partially or entirely different from those of the rock on which they formed. They may have an irregular structure that is thin and obscures details, or they may be thick, homogeneous, and have their own morphological structure. They are usually composed of various salts and oxides. There is a subtype in the form of a black crust.

Black crust: This type of deterioration is commonly observed on stone structures located in urban environments exposed to atmospheric pollution. It forms as a result of sulfur-based acidic gases, together with carbon and tar particles present in polluted atmospheres. The process occurs when atmospheric particulates react with calcium carbonate (CaCO_3) present in carbonate-based stones, dissolving the CaCO_3 and subsequently transforming it either back into calcium carbonate or into gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). During this transformation, other environmental pollutants contribute to the formation of the crust. When the crust develops in a homogeneous manner, it spreads evenly across the surface and may not completely obscure the stone's details; however, when it forms unevenly, it can significantly hinder the perception of surface features. Black crusts usually adhere very strongly to the underlying substrate and may lead to further deterioration phenomena such as flaking, exfoliation, blistering, and granular disintegration (Küçükkaya, 2002, p.100; ICOMOS-ISCS, 2008, pp.42-63; Öcal & Dal, 2012, p.93; Tintin, 2012, pp.44-47).



Figure 1. Black crust (Aykaç Selamoğlu, 2024).

Deposit

Deposits refer to the accumulation of exogenous materials on stone surfaces that are not part of the stone and vary in thickness on the stone surface due to various natural or human factors. Atmospheric pollutants, layers formed by paint and mortar, sea salt aerosols, animal droppings, biologically derived deposits, salt deposits, oxidized metals, or residues of materials used during conservation work are all considered deposits. Deposits forming on the stone surface are characterized by their color, morphology, and size. In most cases, their adhesion to the stone surface is relatively weak (ICOMOS-ISCS, 2008, pp.44-45; Öcal & Dal, 2012, pp.95-96).



Figure 2. Deposit (Aykaç Selamoğlu, 2024).

Encrustation

Encrustation is a hard, mineral-rich crust that chemically accumulates on the surface of the stone. It generally differs from the surface morphology and color

of the stone. This deterioration, also known as incrustation, is firmly attached to the surface of the stone. For this reason, when it is desired to remove it from the stone, material may also be torn from the stone. In advanced stages of crusting, it hardens and forms different shapes such as knots, spheres, and grapes. However, it is defined for distinct situations resulting from accumulation. It is formed by the combination of carbonates, sulfates, metal oxides, or silicates. In other words, the crust covering the surface consists of various salts and oxides. It is usually observed in areas of walls close to the ground where water infiltrates the building stones. Rainwater and carbon dioxide combine to form bicarbonate on the surface of artifacts, causing calcium carbonate precipitation on surfaces where water flows (ICOMOS-ISCS, 2008, p.50; Öcal & Dal, 2012, pp.103-104).



Figure 3. Encrustation (ICOMOS-ISCS, 2008).

Film

A film is generally defined as a thin, homogeneous coating layer of organic origin that forms on the surface of stone. The film may appear opaque or semi-transparent. This layer adheres to the surface but does not penetrate into the stone substrate. For this reason, it can alter surface characteristics such as the color, permeability, and overall appearance of the stone. Certain paint layers as well as water-repellent or protective treatments are considered films. In addition, biofilms may form as a result of biological colonization. Over time, films may lose their semi-transparency and detach from the surface (ICOMOS-ISCS, 2008, pp.52-53).



Figure 4. Film (ICOMOS-ISCS, 2008).

Soiling

Soiling refers to the accumulation of foreign substances on stone surfaces that are unrelated to the stone itself and are considered undesirable both for aesthetic reasons and their potential to damage the material. This form of alteration is mainly associated with atmospheric pollutants such as industrial emissions, domestic combustion products, vehicle exhaust, dust, ash, and soot, as well as the effects of rainwater (ICOMOS-ISCS, 2008, pp.60–61; Odgers & Henry, 2016, p.116). In cases of thin soiling caused primarily by dust, which typically appears in light brown or grey tones, traces of stone tooling may remain visible. Such deposits can usually be removed through gentle dry-cleaning methods, such as brushing with a soft brush. However, when combined with rainwater and atmospheric pollutants, these deposits may contribute to the formation of crusts that pose a risk to the stone surface (Küçükkaya, 2004, p.100). Soiling is particularly common on limestone surfaces and is often observed on building areas exposed to rainfall, where airborne particles adhere to the surface, causing darkening (Odgers & Henry, 2016, p.116).



Figure 5. Soiling (Aykaç Selamoğlu, 2024).

Discolouration

Discoloration is a form of deterioration observed as a change in the color of stone resulting from several processes. These include the chemical decomposition of minerals within the stone structure-particularly the oxidation of iron- and manganese-bearing minerals-the influence of pigments produced by microbiological colonization, and the accumulation of colored substances on the surface. The phenomenon is generally evaluated through parameters such as hue (color tone), value (lightness-darkness), and chroma (color intensity). Subcategories of discoloration include staining, whitening, darkening caused by moisture, and spot formation (ICOMOS-ISCS, 2008, pp.46-63; Öcal & Dal, 2012, pp.97-100).

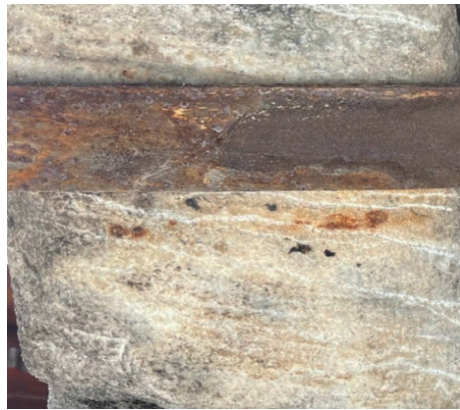


Figure 6. Discoloration (Aykaç Selamoğlu, 2024).

Efflorescence

Salt crystallization occurs as a result of the crystallization of soluble or partially soluble salts located on the stone surface or immediately beneath it. Precipitation, humidity, and water transported through capillary action from the ground carry dissolved chemical substances toward the surface. As temperature increases, this moisture evaporates; following evaporation, the salts transported by the water interact with dust and pollutants present in the environment, forming deposits on the stone surface that may appear colorless, white, yellowish, or black (ICOMOS-ISCS, 2008, pp.48-49; Öcal & Dal, 2012, pp.101-102). Thin accumulations may appear as stains, whereas salts such as sodium, potassium, and calcium nitrates can form thicker deposits that are often removable by brushing (Feilden, 2003, p.107; Odgers & Henry, 2016, p.117).



Figure 7. Efflorescence (Aykaç Selamoğlu 2024).

Biological Colonization

These forms of deterioration occur as a result of the development of microorganisms such as bacteria, algae, lichens, mosses, and fungi on stone surfaces, as well as the growth of plant roots including grasses, shrubs, and trees (Küçükkaya, 2001, p.80; ICOMOS-ISCS, 2008, p.64; Öcal & Dal, 2012, p.110). These organisms grow by using the mineral components of the stone and surface deposits as nutrient sources. Physically, the penetration of roots and fungal hyphae into the stone fabric may lead to cracking and fracturing, while chemically the organic acids and enzymes secreted by these organisms can dissolve the mineral structure of the stone. Such processes accelerate particularly under humid microclimatic conditions and pose a threat to both

the aesthetic appearance and the structural integrity of the stone (Tiano, 2009, pp.3-10; ICOMOS-ISCS, 2008, p.64; Ranalli & Zanardini, 2021, p.218).

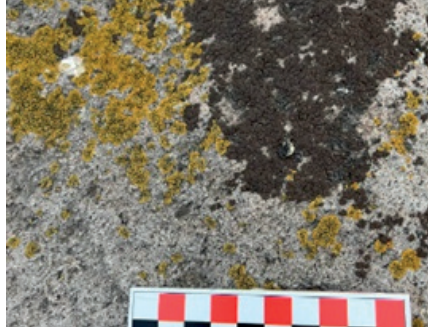


Figure 8. Lichen (Aykaç Selamoğlu 2024).

Cleaning Methods for Stone

In stone monuments exposed to outdoor environments, deterioration phenomena such as dark deposits caused primarily by atmospheric pollutants, salt crystallization originating from the material itself, and biological deposits are frequently observed. The decision to clean these deterioration should be taken carefully, ensuring that the intervention respects the original surface of the material and is applied only when necessary (Eskici, 1997, p.383).

The cleaning of stone artifacts is a complex decision and application process. Deciding which cleaning methods to use requires detailed research. The types and causes of deterioration must be identified before any applications are made. For this purpose, various archaeometric analyses are required. Based on the results of these analyses, the most suitable materials and methods can be selected. These interventions should also be carried out by qualified specialists. Archaeometric tests conducted both before and after cleaning help determine which cleaning methods are the most effective while causing the least damage to the material (Küçükaya, 2004, pp.108-109).

Stone cleaning methods are divided into two groups: mechanical cleaning methods and chemical cleaning methods (Küçükaya, 2004, p.109). Mechanical cleaning methods include cleaning with small hand tools such as scalpels and spatulas (MEB, 2013, p.5), cleaning with atomized and nebulized water spray, and steam cleaning (Eskici, 1997, p.385; Eskici, 2009, p.777), cleaning with dry ice or frozen carbon dioxide aggregate, cleaning with the controlled sandblasting method (Ersen, 2013, p.8), and finally laser cleaning (Küçükaya,

2004, p.114). Chemical cleaning methods include various methods such as packaging with absorbent powders, packaging with solvent-based paper pulp, and cleaning gels (Eskici, 1997, p.386; MEB, 2013, p.3).

Laser Cleaning

Advances in technology and their applications have also attracted considerable interest in the field of cultural heritage conservation (Elhagrassy & Hakeem, 2018, p.44). One of the most significant technological developments in stone cleaning over the past three decades has been laser cleaning. This technique, which has long been used in museums and conservation laboratories, has also begun to be applied in architectural conservation practices and is increasingly becoming widespread (Dajnowski et al., 2009, p.16; Ersen, 2013, p.6). The growing use of laser technology in the field of cultural heritage has led to rapid progress in both scientific research and practical applications.

History of the Use of Lasers in the Field of Cultural Heritage

The first studies concerning the use of lasers for the conservation of cultural heritage were conducted in the early 1970s by the American physicist J. Asmus on the marble surfaces of buildings such as Ca' d'Oro and St. Mark's Basilica in Venice. Subsequently, in the early 1990s, laser cleaning was applied to the façades of several well-known cathedrals in France, including Notre Dame and Chartres. In 1995, within a project supported by CNR-IFAC (National Research Council) and El.En. S.p.A., the use of a laser beam delivered through optical fiber was tested in situ for the first time at the Mausoleo di Teodorico in the Tuscany region near Ravenna.

The growing use of lasers in restoration practices has also led to an increase in research in this field. Recent studies have focused on laser-material interactions, particularly on determining the most suitable wavelength, pulse duration, and energy density for different stone types and applications. As with all cleaning techniques, laser cleaning should not cause morphological or chromatic alterations to the underlying substrate and should ensure efficient ablation. In addition, the method should be easy to apply, economically feasible, and capable of operating under difficult conditions while allowing the laser beam to reach hard-to-access areas (Zanini et al., 2010, p.89).

Since the late 1980s, the use of laser cleaning has become widespread in countries such as Italy, France, the United Kingdom, Portugal, and Austria. Early applications mainly focused on the removal of black crusts caused by urban pollution. Later, the technique was also used to remove layers applied

during previous restoration interventions, such as whitewash, resins, wax, and protective coatings (Siano et al., 2012).

These pioneering applications demonstrated that laser technology allows selective cleaning of cultural heritage surfaces due to its specific physical properties. Therefore, understanding the structure and operating principles of laser radiation is essential for applying this method correctly and in a controlled manner, ensuring that conservation interventions can be carried out without damaging the original material.

Laser Light and the Working Principle of Lasers

Light is an electromagnetic form of energy composed of subatomic particles called photons, which contain both electric and magnetic field components. The fundamental properties of light are defined by wavelength, frequency, and intensity.

Sinusoidal waves oscillating perpendicular to the main axis determine the intensity of light, while the distance between successive peaks along the horizontal axis defines the wavelength. Frequency, also referred to as vibration, represents the number of oscillations occurring within one second. Wavelength and frequency are inversely proportional; as the wavelength increases, the frequency decreases.

The warm white light produced by an ordinary light source is emitted in an unfocused and scattered manner. It falls within the visible wavelength range and consists of a combination of multiple colors within the visible spectrum. Laser light, in contrast, produces a monochromatic, coherent, and highly collimated beam (Kasnak & Fıratlı, 2016, p.2).

Due to these properties, a laser beam can deliver high energy concentrated in a small area, enabling controlled effects on the surface. The generation of laser radiation requires several key components: an active medium, a pumping mechanism, a fully reflective mirror, and a partially reflective mirror. The active medium consists of atoms that can be excited to higher energy levels by an external stimulus. Various materials such as gases, solid crystals, and semiconductors are used to form this medium. The pumping mechanism provides energy to the active medium through chemical, optical, or electrical means.

The fully reflective mirror reflects all incident light, while the partially reflective mirror allows a portion of the light to pass through. These components are located within the optical cavity of the laser device. One end of the cavity contains the fully reflective mirror, while the other contains the partially

reflective mirror. The mirrors cause light to travel back and forth within the cavity, and with each pass the energy of the light increases. When the active medium reaches a saturation level, the amplified light exits through the partially reflective mirror as a laser beam (Kasnak & Firatlı, 2016, p.2).

Laser systems developed according to these principles offer important advantages for the conservation of stone surfaces, particularly through selective cleaning, controlled ablation, and high precision. These advantages have led to the increasing use of laser techniques in surface cleaning applications in recent years. Among the various laser technologies, solid-state lasers are among the most frequently used systems.

Solid-State Lasers

Solid-state lasers generally operate in two different pulse regimes: Free Running (FR) and Q-Switched (QS) modes. In free-running lasers, the laser output approximately follows the temporal profile of the pumping light and produces relatively long pulses ranging from 200 microseconds (μs) to several milliseconds (ms). In Q-switched lasers, however, the pulse duration is significantly shorter, typically between 1 and 100 nanoseconds (ns). These short pulses generate very high energy densities on the stone surface, enabling rapid ablation, i.e., the removal of material. Both methods present certain advantages and disadvantages (Zanini et al., 2010, pp.90-91).

Q-switched lasers generally exhibit higher ablation efficiency compared with free-running systems, and their pulse spot size is smaller. This allows for more precise removal of dirt or crust layers. However, the intense shock waves generated by QS lasers may not only fragment thick crust layers but also potentially produce microcracks or superficial fractures in the substrate. Although such effects are often difficult to detect visually, controlling these thermal and mechanical shocks is one of the most critical aspects of cleaning operations performed with short-pulse lasers (Zanini et al., 2010, pp.90-91). Among solid-state laser systems, the Nd:YAG laser is the most widely used for cleaning stone surfaces.

Nd:YAG Laser Systems

Due to its relatively low cost, high reliability, and availability across a wide range of power outputs, the Nd:YAG laser has long been widely used in the conservation of artworks. Its solid-state structure makes it a compact and portable system, suitable for both laboratory and on-site applications.

Nd:YAG lasers typically operate in pulsed mode, allowing precise control of the energy delivered in each pulse and ensuring that the energy applied to the surface during cleaning remains within safe limits. The energy source is usually a flash lamp, although diode-pumped solid-state lasers (DPSSL) have also been developed. These systems offer greater efficiency, generate less heat, and provide more stable performance (Abraham & Twilley, 1997, pp.8-11).

Laser operating modes include Q-switch (short pulse) and long-pulse regimes. The Q-switch mode provides high energy density and is effective for removing thick crusts or resistant deposits on stone surfaces. The long-pulse mode, on the other hand, produces safer results when cleaning delicate surfaces such as gilded layers. In some applications, wavelengths other than the fundamental 1064 nm infrared wavelength may also be used (Abraham & Twilley, 1997, pp.8-11).

Cleaning by Laser Method

In the conservation of cultural heritage, it is essential to use cleaning methods that are both effective and minimally invasive, particularly when dealing with surfaces of historical and artistic significance. Laser cleaning is among the techniques that have produced highly positive results on a wide range of surfaces, including stucco decorations (Zanini, 2010, pp.90-91).

Laser systems offer four principal advantages. The first is their non-contact operation, which allows work to be carried out even on fragile surfaces prior to consolidation, thanks to the minimal dispersion of the beam. The second advantage is their high level of controllability. During the removal of unwanted layers, the system can be calibrated so that each pulse removes only a few microns of material, enabling extremely precise control over the depth of cleaning. Another advantage is the high level of precision achieved during operation. The cleaning process affects only the area directly targeted by the laser beam, without causing mechanical or thermal effects on the surrounding regions. Laser systems equipped with fiber-optic delivery further facilitate the cleaning of complex or hard-to-reach surfaces. In addition, the use of a variable-focus handpiece allows flexible operation on both large surfaces and extremely fine details. The final advantage is selectivity. Laser cleaning relies on differences in light absorption related to the color of materials. Dark or black deterioration layers absorb the laser energy efficiently and are rapidly removed, whereas lighter surfaces or protective patinas reflect the radiation, thereby limiting or delaying the laser's effect (Zanini, 2010, pp.90-91).

For these reasons, laser cleaning has become one of the most advantageous methods for removing pollution-induced deposits from architectural stone

surfaces. Compared with many other cleaning techniques, it generally produces less damage while remaining highly effective, making it a particularly useful tool in the conservation of stone heritage (Zanini, 2010, pp.90-91).

International Case Studies

In recent years, laser cleaning has been widely applied in various restoration projects across different regions for the conservation of stone cultural heritage. A review of the literature indicates that laser cleaning applications have been particularly concentrated on architectural façades, where various deterioration phenomena occur. Although a significant portion of these applications has been carried out in Europe, laser technology has also been employed in the cleaning of cultural heritage materials in many parts of the world, under diverse climatic conditions and on different stone types.

In this section, four case studies from different countries demonstrating the use of Nd:YAG laser cleaning in the conservation of stone cultural heritage are examined. These include the Church of Maddalena in Italy, St. Stephen's Cathedral in Austria, the Patan Royal Palace in Nepal, and Chartres Notre-Dame Cathedral in France. These examples enable a comparative evaluation of the effectiveness and limitations of Nd:YAG laser cleaning on different stone types and surface layers.

Stone Types and Deterioration Conditions

The examined case studies demonstrate that laser cleaning may exhibit different responses depending on the type of stone involved. In particular, the removal of black crust layers formed on carbonate stone surfaces represents one of the most successful areas of application for laser cleaning.

In the selected case studies, investigations carried out on the façade elements of the Church of Maddalena in Venice revealed that the stone elements consist of fine-grained Istrian limestone, on which extensive black crust formations were observed. Detailed analyses also identified several additional forms of deterioration accompanying the black crusts, including yellow-brown patina, surface soiling, salt crystallization, biological colonization, and calcium oxalate patinas (Figure 9). In addition to these deterioration layers, residues of linseed oil and calcium carbonate coatings from previous restoration interventions were detected in certain areas. It was further confirmed that the stone surfaces beneath the oxalate patina layers were generally well preserved, indicating that this patina can provide a certain protective effect on the underlying stone (Armani et al., 2000, pp.100-101).

For this reason, it is essential to distinguish between deterioration forms that damage the integrity of the stone and patina layers that may play a protective role, ensuring that cleaning interventions are carried out selectively.



Figure 9. Distortion in the eye motif above the entrance door (Armani et al., 2000).

Investigations conducted at St. Stephen's Cathedral in Vienna determined that the stone material used in the structure is sandstone, and that the surfaces had undergone deterioration in the form of gypsum- and carbon-based black crusts as a result of prolonged exposure to atmospheric conditions (Figure 10) (Calcagno et al., 2000, p.111). These crusts not only disrupt the aesthetic integrity of the stone surfaces but also accelerate the deterioration processes of the material.



Figure 10. Main Roman portal, lunet with Pantokrator Jesus and angels: Before laser cleaning (Calcagno vd., 2000).

Studies conducted on the stone doors of the Patan Royal Palace in Nepal revealed that the material consists of fine-grained quartz sandstone, on which deterioration phenomena such as biological colonization, salt crystallization, scaling, and exfoliation were observed. In addition, dark and opaque surface layers were identified on the doors (Figure 11).

Detailed analyses of these layers indicated that they were the result of a bituminous restoration product. It was determined that these coatings not only altered the appearance of the surfaces but also modified the surface behavior of the stone, thereby contributing to further deterioration (Fuchs et al., 2014, pp.187-188).



Figure 11. Gate A (North) pre-conservation condition (Fuchs et al., 2014).

In the final case study, conducted at Chartres Notre-Dame Cathedral, black crust formations and a protective oxalate layer were identified on the limestone surfaces (Vergès-Belmin et al., 2015, pp.14-17). This situation represents a case in which selectivity in cleaning and the risk of color alteration must be evaluated together during the intervention process.

Laser Systems and Applications

In most of the studies examined, Nd:YAG laser systems were used for stone cleaning. These systems are widely preferred in restoration practices because they allow the selective removal of surface deposits formed on stone surfaces.

In the applications carried out at the Church of Maddalena, the Art Master Laser system was used in order to remove black crusts and surface dirt layers in a controlled manner. This system, based on Nd:YAG laser technology, operates with a wavelength of 1064 nm, a pulse duration of approximately 9 ns, and a repetition rate of up to 12 Hz. At the end of a 60-day application period, deterioration forms such as black crusts and surface soiling were

successfully removed in a controlled manner from approximately 140 m² of stone surface (Figure 12) (Armani et al., 2000, pp.102-104).



Figure 12. Cleaning of the lunet detail above the inlet (Armani et al., 2000).

In the applications conducted at St. Stephen's Cathedral, Nd:YAG Q-switched laser systems, again using the Art Master Laser, were employed. During the intervention, six laser devices were used, and the systems were adjusted to operate with short pulse durations of approximately 10 ns in order to minimize thermal effects on the surface. The beam diameter was carefully controlled based on previous experimental experience. In addition, various parameters were tested during the cleaning of deterioration layers with different thicknesses and surface characteristics. This allowed the intervention to be carried out in a controlled, gradual, and precise manner, preventing phenomena such as melting, oxidation, or the formation of microcracks on the surface (Figure 13) (Calcagno et al., 2000, pp.115-116).



Figure 13. Main Roman portal, lunet with Pantokrator Christ and angels: After laser cleaning (Calcagno et al., 2000).

In the restoration works initiated in 2010 on the doors of the Patan Royal Palace, laser cleaning was primarily applied to remove the bituminous coating layer present on the stone surface. Test applications demonstrated that under specific parameters the laser system could remove the coating layer in a controlled manner without damaging the stone substrate. Based on these results, the modified Laser Eos 1000 LQS, operating at a wavelength of 1064 nm, was selected as the most suitable equipment for the cleaning process (Fuchs et al., 2014, pp.188-191).

In the LQS system, operational parameters such as energy, energy density, frequency, and spot diameter could be precisely adjusted, thereby reducing the risk of photomechanical damage or color alteration. It was also observed that slightly moistening the stone surface with water improved both the effectiveness and the gradual nature of the cleaning process. After the intervention, the bitumen-based coating was largely removed from well-preserved and slightly weathered surfaces, leaving only small residues within the pores (Figure 14). As a result, the decorative elements became readable again. However, in areas with high porosity, significant deterioration, and weak sedimentary layering, the bitumen had penetrated several millimeters into the stone, which limited the effectiveness of the cleaning process. In addition, complex surface geometries made it difficult for the laser beam to reach all areas of the surface (Fuchs et al., 2014, pp.188-191).



Figure 14. The condition of one of the sculptures during laser cleaning and after the bitumen removal was completed. (Fuchs et al., 2014).

At Chartres Notre-Dame Cathedral, applications were carried out to remove black crusts from limestone surfaces. Earlier interventions on the sculptures located in the portals of the north transept had already involved laser cleaning using Nd:YAG Q-switched (QS) NL102 lasers (1064 nm) produced by BM Industries. Although this method produced satisfactory results in terms of preserving sculptural details, noticeable color differences appeared between the

yellow-light brown tones of the laser-cleaned sculptures and the color of the surrounding architectural elements. For this reason, during the interventions conducted in 2012 on the previously uncleaned south transept portal, it was decided to test new laser systems. The company El.En. provided the Combo laser system for a one-week trial. Two operating modes of the Nd:YAG (1064 nm) laser were compared; long Q-Switched (LQS) mode, with pulse durations reaching 100 nanoseconds and short Free Running (SFR) mode, with pulse durations of approximately 100 microseconds. In the LQS mode, with an output energy of 150 mJ and a pulse frequency of 10 Hz, the cleaning process was faster. The oxalate layer was preserved during cleaning, and the black crust was completely removed (Figure 15). However, this mode also produced a more pronounced yellowing effect on the surface. Similar results had previously been observed in applications using QS lasers in 2002. In the SFR mode, the higher energy output resulted in lower cleaning efficiency. Although the oxalate layer was again largely preserved, some portions of the black crust could not be fully removed from the surface. Nevertheless, the degree of yellowing was lower in SFR mode (Vergès-Belmin et al., 2015, pp.14-17).

Consequently, it is considered premature to determine a definitive cleaning method for the still uncleaned portals of Chartres Cathedral, as a significant dilemma exists. LQS or QS laser modes are the most suitable methods for preserving micrometric carving details and traces of previous workmanship, but they tend to cause color alteration (yellowing). Although SFR mode is slower, it may be applicable at Chartres if an appropriate energy density is selected that ensures the preservation of surface layers. It has therefore been suggested that the SFR mode should be tested on larger surfaces (Vergès-Belmin et al., 2015, pp.14-17).

These studies demonstrate that the parameters used in laser cleaning must be carefully determined according to the type of stone and the characteristics of the surface deposits present on it.



Figure 15. Cleaning results in a portal of the northern transept: The sculptures were cleaned with Nd:YAG Q-switched laser devices (Vergès-Belmin, et al., 2015).

Conclusion

This study is a review that examines application examples selected from four different countries in order to evaluate the potential of laser cleaning methods in the conservation of stone cultural heritage that have suffered deterioration due to various factors and consequently lost both aesthetic and structural integrity. The examined studies demonstrate that Nd:YAG laser technology provides high levels of selectivity, precision, and controllability, particularly in the removal of deterioration layers such as surface soiling and black crusts. Controlled ablation applications carried out especially at a wavelength of 1064 nm and within low to medium fluence ranges have shown that dirt and crust layers can be safely removed without damaging the original stone surface.

In the case of the Church of Maddalena, the preservation of the oxalate patina to a large extent, and in St. Stephen's Cathedral, the ability to remove black crusts while maintaining the original stone texture, demonstrate that laser cleaning can be applied in accordance with the principle of minimum intervention. In the example of the Patan Royal Palace, it was observed that the bituminous coating layer could largely be removed when appropriate parameters were applied. However, in areas with high porosity and advanced deterioration, the effectiveness of cleaning was limited due to the penetration of the coating layer into the stone matrix.

Nevertheless, the success of laser cleaning depends on many variables, including the mineralogical composition of the stone, surface texture, type of deterioration, and the adhesion of the deposit layer. For this reason, in each

application it is essential to determine parameters specific to the stone artifact-such as energy density, pulse duration, and spot diameter-to conduct preliminary tests on sample surfaces, and to ensure that the operator has sufficient expertise in the method. When inappropriate parameters are selected, undesirable effects such as yellowing or browning, particularly on calcite-containing surfaces, may occur. In the case of Chartres Notre-Dame Cathedral, although the QS and LQS modes preserved fine details, the risk of yellowing was observed; conversely, longer pulse durations reduced the degree of yellowing but also decreased cleaning efficiency.

Overall, laser cleaning stands out as a method compatible with internationally accepted scientific and ethical conservation approaches, as it can be applied without physical contact with the surface, allows micrometric control over the removal depth of surface layers, provides high selectivity, preserves the original material, and can be faster and more economical than conventional methods. For these reasons, it represents an increasingly important technique for the sustainable conservation of cultural heritage.

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